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PL-TR-92-2071
Special Reports, No. 269

A HISTORY OF THE SPACE RADIATION EFFECTS (SPACERAD) PROGRAM FOR THE JOINT USAF/NASA CRRES MISSION.

Part I: FROM THE ORIGINS THROUGH THE LAUNCH, 1981-1990

Ruth P. Liebowitz

16 March 1992

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92-12894

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
16 March 1992

3. REPORT TYPE AND DATES COVERED
Scientific Interim

4. TITLE AND SUBTITLE
A History of the Space Radiation Effects (SPACERAD) Program for the Joint USAF/NASA CRRES Mission Part I: From the Origins through the Launch, 1981-1990.

5. FUNDING NUMBERS
9993TSXX

6. AUTHOR(S)
Ruth P. Liebowitz

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Phillips Laboratory/ TSR
Hanscom AFB, MA, 01731

8. PERFORMING ORGANIZATION REPORT NUMBER
PL-TR-92-2071
SR, No. 269

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release: distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

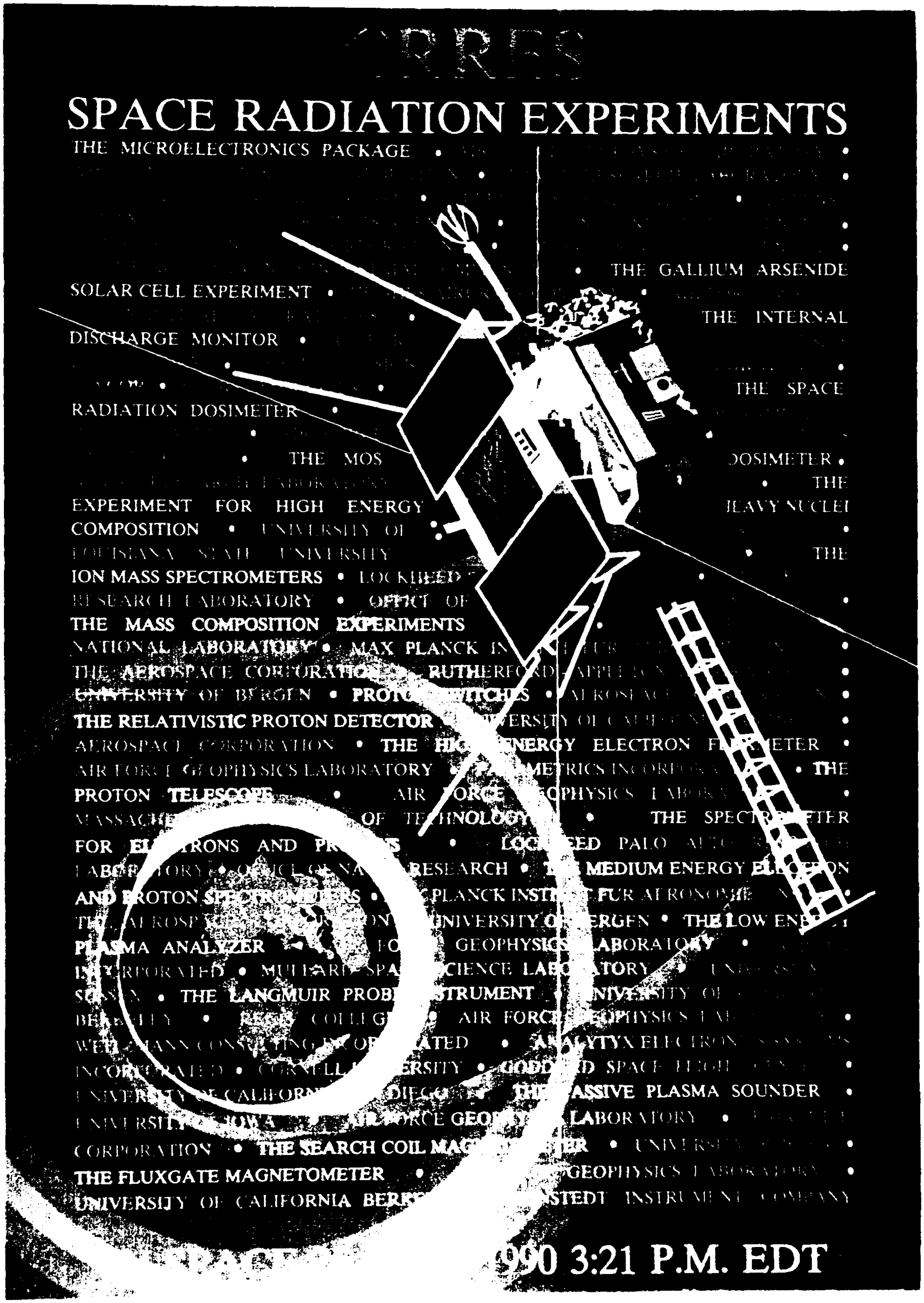
The history narrates the Space Radiation Effects (SPACERAD) Program from its origins in 1981 through the launch of the SPACERAD experiments on the USAF/NASA Combined Release/Radiation Effects Satellite (CRRES) on July 25, 1990 and the initial data results in October 1990. The SPACERAD Program comprised a coordinated schedule of space-and-ground testing of state-of-the-art microelectronics, together with new satellite measurements of the Earth's radiation belts. The goals for the program were to produce improved standards and procedures for ground-testing future space microelectronics and new dynamic models of the radiation belts. The history discusses programmatic, management and funding issues that arose in the course of its realization.

14. SUBJECT TERMS
Solar Radiation
Microelectronics
Magnetospheric Physics
Satellite Experiments
Radiation Hardening

15. NUMBER OF PAGES
68

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR



SPACE RADIATION EXPERIMENTS
THE MICROELECTRONICS PACKAGE
THE GALLIUM ARSENIDE
SOLAR CELL EXPERIMENT
THE INTERNAL
DISCHARGE MONITOR
THE SPACE
RADIATION DOSIMETER
THE MOS
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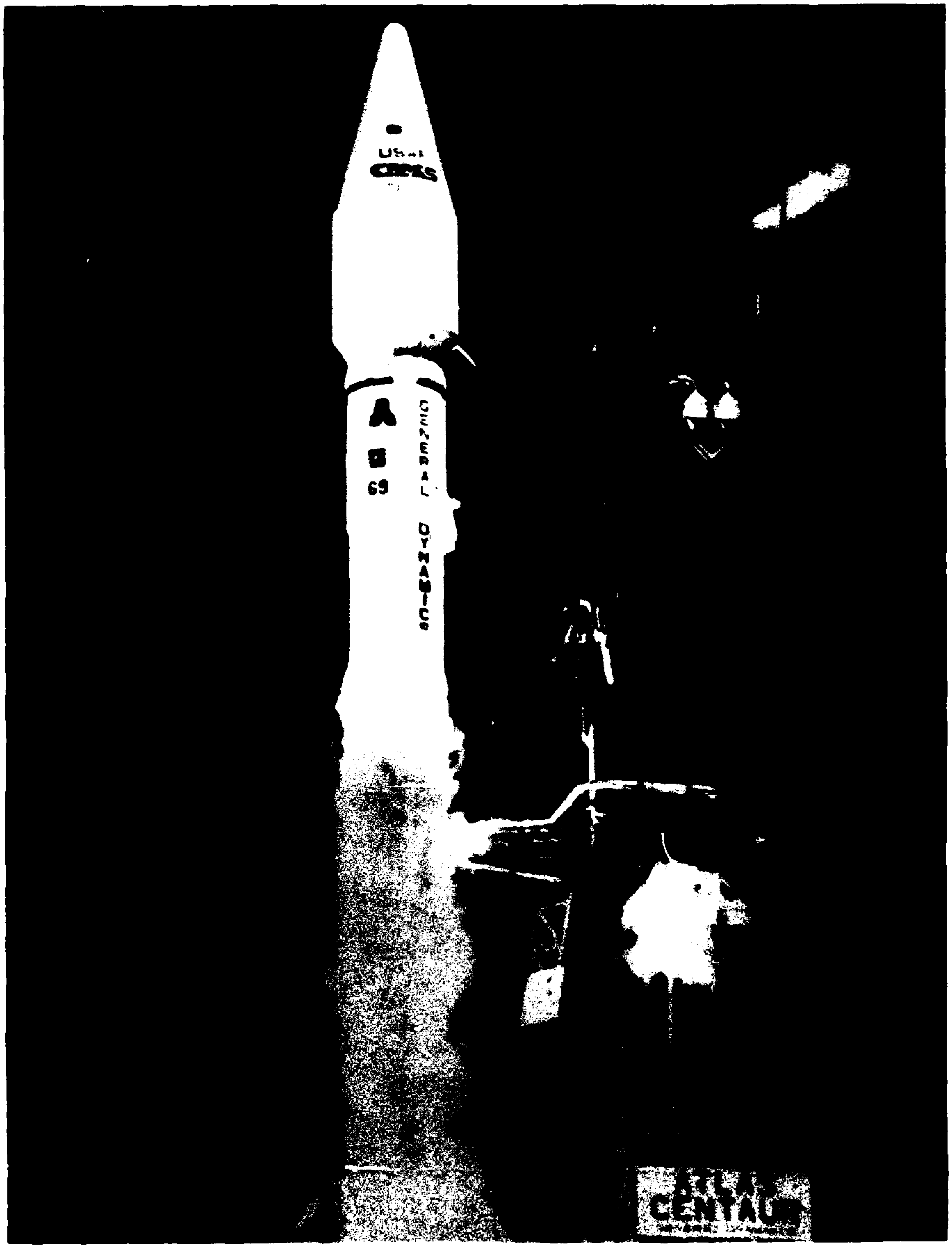
PREFACE

The history that follows presents a account of the Space Radiation Effects (SPACERAD) Program from its beginnings in the early 1980s to the successful launch of the SPACERAD experiments on the USAF/NASA Combined Release/Radiation Effects Satellite (CRRES) on July 25, 1990. It is the history of the DoD segment of a joint-agency scientific satellite program. The account is written from the working-level perspective of the participating experimenters located at the Air Force Geophysics Laboratory (AFGL), recently redesignated the Geophysics Directorate of Phillips Laboratory.

Since 1983 the AFGL Historian has been "riding along" with the SPACERAD program, periodically interviewing Edward G. (Gary) Mullen, its Program Manager, and other members of the team, and collecting documentation on the whole CRRES/SPACERAD mission. Part I of the *SPACERAD History* represents the summation of this ongoing, in-house, effort through the launch and initial data results (October 1990). A second volume, Part II, will deal with CRRES operations during the satellite's lifetime (July 1990-October 1991), the reduction and analysis of the data from the SPACERAD experiments, and the end-products (models, testing standards) to come out of the program.

The Historian wishes to express her appreciation to Gary Mullen and all the other persons interviewed who kept her abreast of developments in the SPACERAD program and helped to elucidate technical issues. She also thanks Ms. Evelyn Kindler who incorporated revisions and edited and proofread the final version of the text.

Ruth P. Liebowitz
Hanscom Air Force Base, MA
January 1992



CRRES launch from Cape Canaveral, FL, July 25, 1990

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Accession For	
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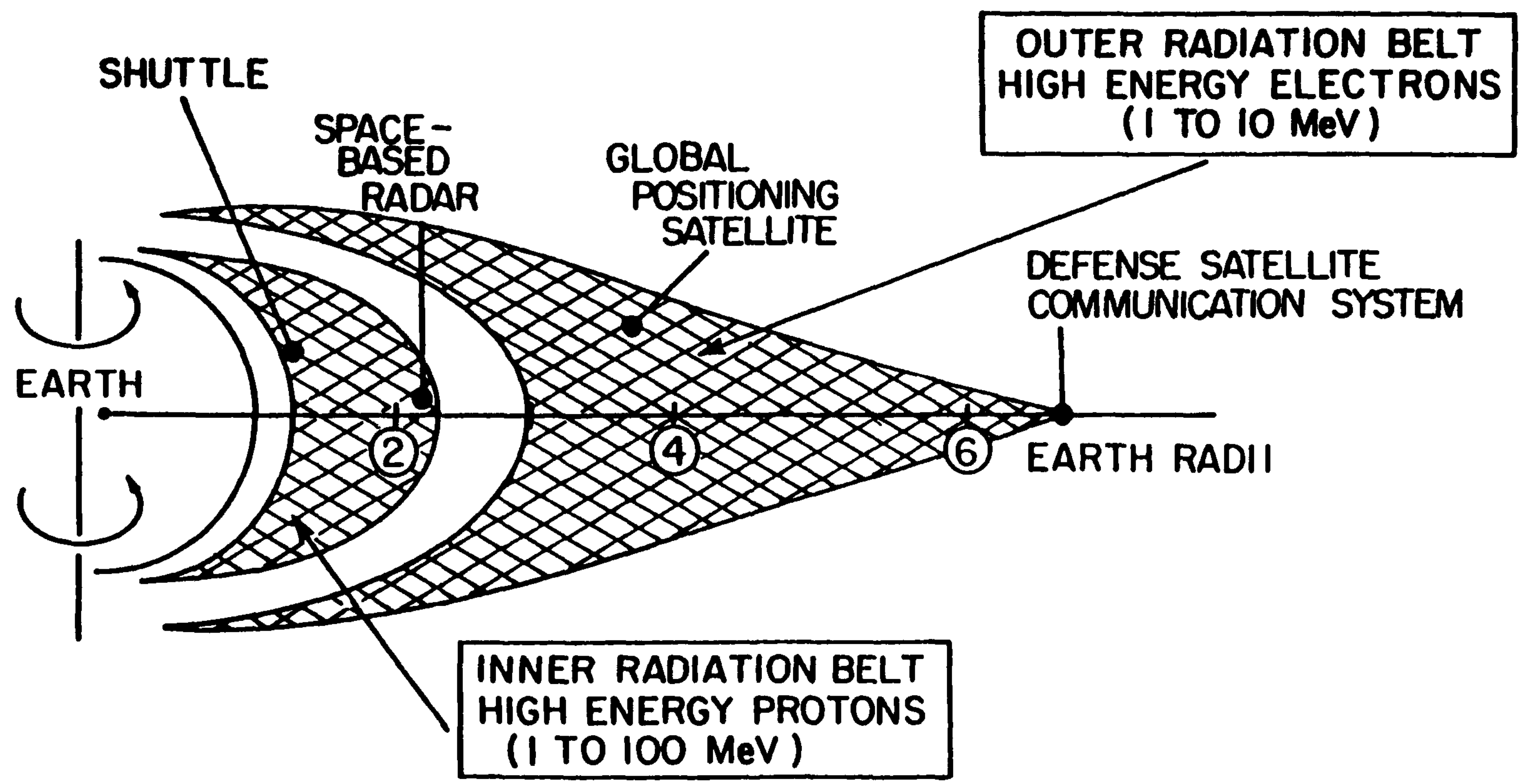
THE SPACE RADIATION EFFECTS (SPACERAD) PROGRAM

The Challenge of Space Radiation

For military planners the survivability of microelectronics systems in space is a serious issue. The need for radiation hardening of microelectronics has become even more crucial with the strategic goal of creating autonomous spacecraft which will rely on information processing on-board the vehicle. There are different requirements for hardening against natural and nuclear conditions. In the case of natural conditions, there are high-energy particles in near-Earth space that can affect space systems. These include particles emanating from the Sun during solar proton events, cosmic rays, and high-energy radiation particles trapped in "belts" around the earth. (The latter have been named the Van Allen belts in honor of James A. Van Allen who led the team that discovered them in 1958.) Particles trapped in the inner (primarily proton) and outer (primarily electron) radiation belts can damage advanced electronic devices and other systems on board spacecraft. Their susceptibility to damage has increased as the size of microelectronic cells has decreased.

Exposure to energetic, charged particles is known to damage satellite systems in several ways. In microelectronic components, a single, high-energetic particle traversing a device or initiating a nuclear reaction within it can upset its logic state causing errors in program execution -- a single-event upset (SEU). These errors can often be eliminated by resetting or reinitializing the system ("soft" errors), but sometimes they are unrecoverable ("hard" errors). Over time electronic devices may also gradually become degraded due to exposure to radiation. The amount of degradation depends both on the total dose and on the dose rate of irradiation.

RADIATION BELTS



Depending on the device's susceptibility to radiation and the environment experienced, devices may last only a few days or many years. Electronic circuits may also be adversely affected by discharges from accumulated high-energy electrons in dielectric materials on the spacecraft. Arcing of the stored charge to conducting materials can produce large voltage pulses which may cause components to be upset or damaged.

These deleterious effects are a cause of concern for the whole spacecraft operations community. Because of the extent of the radiation belts (see the diagram, page 2), they can create problems for communications and weather satellites out at geosynchronous orbit, such as the Defense Satellite Communications System (DSCS) and the Geostationary Environmental Satellites (GOES), and also for lower-altitude satellites in polar orbit, such as the Defense Meteorological Satellite Program (DMSP). NASA's first Tracking and Data Relay Satellite System (TDRSS), for instance, experiences an average two SEU's per day. As a result, the logic software has to be reloaded daily.[1] A Space Shuttle flying in a high-inclination orbit often traverses the lower portion of the inner radiation belt and can be exposed to solar protons during large solar disturbances. Only spacecraft in low-altitude equatorial orbits escape the effects of the radiation belts.

Achieving appropriate shielding from natural radiation for microelectronics is a complex endeavor. It requires, first of all, an accurate knowledge of the radiation levels in the different parts of the belts. The NASA (Vette) models[2] of the radiation belts which are currently used for shielding calculations are static models. They do not take into account the dynamic fluctuations of the belts with their underlying processes of filling, transport, and dumping. These models are based on data from the 1960s and 1970s, which are of uneven quality and may be partly colored by the effects of the nuclear tests of the early 1960s. They are also uneven in spatial distribution, which means that radiation values for some areas in the belts are largely an extrapolation.[3]

A second major issue in shielding is the "bremsstrahlung" effect. Laboratory tests have shown that when shielding for a system is increased beyond a certain point, the secondary radiation produced in the shielding by the primaries increases, actually leading to higher doses of the radiation. Thus the optimum shielding for a given system in a given orbit is a balance between these two effects. Because of the difficulty of determining this balance, the approach to shielding in practice has often been to adopt the amount of shielding whose total weight is affordable. However, as the continuing occurrence of anomalies in signals transmitted from various spacecraft and the occasional disabling of satellite sensors testify, this approach does not always provide protection. In some instances, shielding the whole spacecraft precludes augmenting the instrumental capability for the mission. A generally more cost-effective approach is to harden individual chips and components to be used in space, but this involves identifying an appropriate amount of shielding for each type.[4]

The goals of the Air Force's Space Radiation Effects (SPACERAD) Program are to develop dynamic radiation belt models and help define realistic standards for the ground testing of microelectronic components, which will guarantee effective and reliable shielding in space.

Radiation Satellite (RADSAT), 1981

In 1981 the Air Force Geophysics Laboratory proposed a major new R&D satellite program whose primary goal was to obtain a comprehensive data base on the charged energetic particle environment in order to create better models and thus increase spacecraft survivability. It also planned to measure the degradation and soft error rate of a number of advanced microelectronic devices in the space environment. These included some types already in use, such as CMOS devices, and others under development, like gallium arsenide and VHSIC (very high speed integrated circuit) components. An on-board microcomputer would measure the effects of incoming radiation on the components' performance while other instruments were simultaneously taking extensive measurements of the radiation itself. In order to measure all sectors of the space environment, the satellite would follow a highly elliptical orbit passing through both the inner and outer regions of the Van Allen belts approximately every ten hours. At perigee it would fly in close to the Earth's atmosphere, while at apogee it would go beyond the belts into the outer magnetosphere. The results of the program would be of use to all DoD agencies operating spacecraft, to the National Aeronautics and Space Administration (NASA), and to the aerospace industry. This new program was entitled RADSAT (Radiation Satellite) in the expectation of obtaining a dedicated satellite for it.

The Laboratory's experimental space programs were usually flown under the Air Force Space Test Program (STP), operated by the Air Force's Space Division in Los Angeles, CA. In this instance, the new RADSAT program took over the STP experiment number AFGL-701 from a more limited, earlier AFGL effort along similar lines, which was entitled Environmental Effects on Space Systems (E^2S^2). Although the RADSAT Program had a single-number designation under the Space Test Program, it comprised a set of 18 interrelated experiments. The approach of the program, as detailed in the lengthy 1981 Space Flight Request (DD Form 1721), was to combine all the Air Force experiments currently proposed by AFGL and the Aerospace Corporation that aimed to measure charged particles in space. In order to achieve an increased scientific thrust, complementary experiments from the Office of Naval Research (ONR), the Naval Research Laboratory (NRL), and NASA were added, making the effort a tri-agency program.[5]

The RADSAT instruments embodied the capability of measuring all the particles to be found in the radiation belts. They were designed to detect electrons, protons, and ions across a wide energy range from a few eV to hundreds of meV. A complementary group of instruments was to measure the fields (electric and magnetic) and plasma waves which affect the distribution of trapped energetic particles. Lastly, RADSAT included a package containing microelectronic components, instruments to record types of radiation-damage suffered by the components, and dosimeters to measure shielding effectiveness. In order to define outstanding problems related to trapped radiation, AFGL held an international scientific conference on the subject on 26-27 January 1981.[6]

The goal of a large experimental program with a dedicated satellite was advocated by Rita Sagalyn, Chief of the Plasmas, Particles, and Fields Branch. (In 1982 she became Director of AFGL's Space Physics Division.) This represented a major shift in approach to space experiments from the Laboratory's practice of the 1960s and 1970s when single or small groups of instruments were prepared to await rides of opportunity.[7] By the later 1970s this approach was becoming less attractive. Some of the simpler experiments had already been done, the number of satellites available for "piggy-backing" had diminished, and government resources were now devoted to developing the Shuttle as the national launch vehicle. In 1979 the Optical Physics Division at AFGL had proposed a large-scale experiment for flight on the Shuttle, the Cryogenic Infrared Radiance Instrument for Shuttle (CIRRIS). The RADSAT Program was a similarly scaled proposal for a free-flying satellite. During fiscal year 1981 AFGL was negotiating through its West Coast Office with the Space Test Program in order to obtain funding for a satellite and a vehicle to launch it into orbit. The STP Office had planned for RADSAT to be paired for launch with a Defense Satellite Communications System (DSCS) III satellite using a spare DSCS II bus. In November 1981 these plans fell through because of cuts in the STP budget for fiscal year 1982. This made it impossible for RADSAT to meet the DSCS III launch date, and so the program was left without a launch vehicle.

In this discouraging situation, AFGL looked about for alternative launch vehicles and program strategies. One event in RADSAT's favor was the realization about this time by Space Division that there would be a lag in the development of space-hardened microelectronics needed for planned space missions. Responding to this requirement, AFGL started to increase its emphasis on the engineering experiments in RADSAT. It proposed expanded efforts to measure the effects of space radiation on microelectronics and a complementary ground test program.[8] Basically, by undertaking to work within and through a more complex program with the primary emphasis on space microelectronics and system design, the Laboratory hoped to gain high-level support for carrying out comprehensive studies of the radiation belts.

This approach proved successful. The Deputy for Technology at Space Division issued an Advanced Development Program Plan for Space Hardened Electronics in January 1982 which included participation by AFGL. At the same time, General Robert T. Marsh, the commander of Air Force Systems Command, recommended that RADSAT be scheduled for a new start using an expendable booster or the Shuttle.[9] Two months later AFGL changed the name of its program from RADSAT to SPACERAD (Space Radiation Effects) to have it embody the new scope and thrust of the enterprise.

The Combined Release/Radiation Effects Satellite (CRRES), 1982

Early in 1982 the AF Space Test Program explored with NASA the concept of a joint DoD/NASA satellite mission -- the Combined Release/Radiation Effects Satellite (CRRES). This satellite would fly the NASA Chemical Release Program, which had also suffered cuts, and the Air Force's SPACERAD experiments in a single cost-saving mission. The launch vehicle for the CRRES satellite was to be the Space Shuttle. It was proposed that the Air Force would fund the spacecraft development, while NASA would cover the "transportation," i.e. the cost of Shuttle integration and launch. To accommodate diverse experimental goals, the satellite would fly the NASA experiment in low-earth orbit for a period of about two months. Then it would be boosted into a highly elliptical orbit traversing the radiation belts for Air Force experiments, which were expected to last three to five years.

These plans gained high-level support from both the Air Force and NASA, enabling the CRRES Program to move forward.[10] Ball Aerospace Systems Division, the contractor for NASA's Chemical Release Program, was retained to fabricate the CRRES satellite and to integrate its payload. The CRRES Experimenters Working Group which consisted of the major Air Force and NASA participants, had its first meeting in Los Angeles in May 1982. Experiment requirements, payload definition, and preliminary data management plans were negotiated. In September, at the end of fiscal year 1982, AFGL signed a preliminary Memorandum of Agreement (MOA) with the Air Force Space Test Program for the integration and spaceflight of the SPACERAD experiments. Subsequently, higher level MOAs for the CRRES Program were signed between the AF Space Test Program and NASA/Huntsville and between NASA headquarters and the Pentagon. The AF Space Test Program was designated the manager of the DoD part of the mission, and it gave CRRES the official experiment number, P86-1.[11]

The DoD segment of the CRRES Program took definite shape over the course of 1982. SPACERAD's primary goal was to develop controlled testing for radiation effects on selected microelectronic components and chips, and the measurements of the radiation belts were linked into this concept. A Microelectronics Working Group composed of experts on radiation hardening from DoD Laboratories, NASA, the Jet Propulsion Laboratory (JPL), Sandia National Laboratories, Aerospace Corporation, universities, and industry was formed. The Group had its first meeting in June 1982. Out of its investigations and discussions during the latter part of 1982 came the "Proposal for a Space Radiation Effects Experiment and Test Program."

The proposal called for initial ground testing in order to determine radiation levels for single event upsets (SEU) and to study both total dose and dose rate effects. The results would then be analyzed and modeled. This ground phase was to be followed by space testing on the CRRES satellite of an identical set of components together with simultaneous measurements of the radiation belts. These satellite data would be used to verify and update the ground-test models. End products of the program would include dynamic models of the radiation belts, design standards for shielding components in space, and procedures for testing of components.[12] A consortium of DoD and civilian sponsors (including NASA, DARPA, the Navy, and the Defense Nuclear Agency) agreed to provide funding for the SPACERAD engineering experiments and the ground testing program, while AFGL and the other original RADSAT participants contributed funds for the environmental sensors.

A second and much smaller group of DoD experiments for CRRES (NRL-701) coalesced in 1982. It included instruments from the Naval Research

Laboratory, AFGL's Ionospheric Physics Division, and the Aerospace Corporation. They were to make low-altitude satellite studies of ionospheric irregularities (hence the acronym, LASSII) during the low-earth orbit phase of the mission.

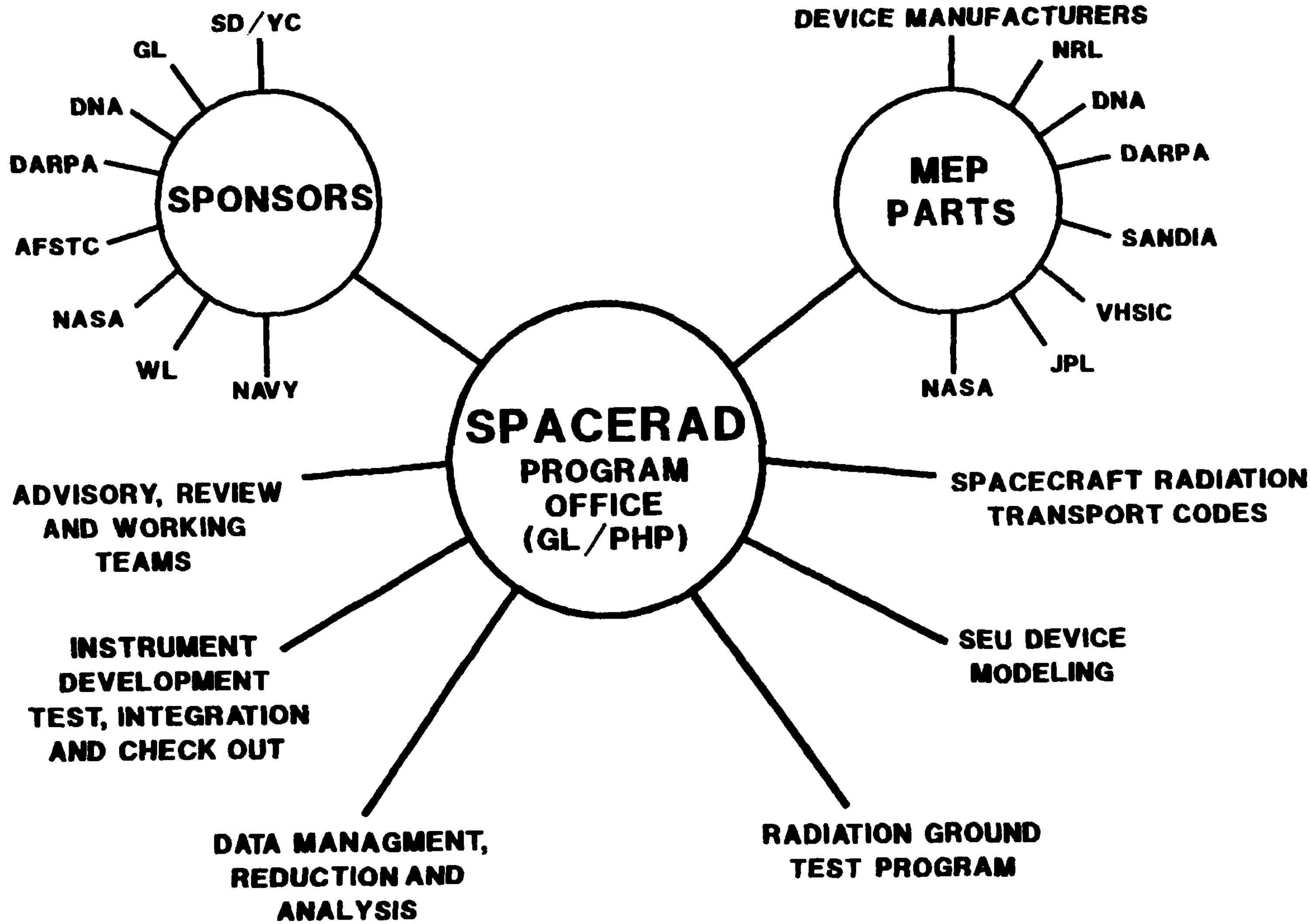
The NASA segment of the mission consisted of a set of Chemical Release experiments for both the LEO and GTO orbits. Utilizing releases in the first orbit, the objectives were to further their understanding of the interaction of plasmas with the earth's magnetic fields, the coupling of the upper atmosphere with the ionosphere, the structures and chemistries of the ionosphere, and conditions in the ionosphere that may affect communications. The releases performed in the magnetosphere during the GTO phase were to study the formation of diamagnetic cavities, coupling between the magnetosphere and ionosphere, and the effects of artificial plasma injections upon the stability of the trapped particles in the radiation belts. On 27 May 1983 NASA issued an Announcement of Opportunity out of which specific chemical release experiments and associated ground and airborne diagnostics were selected for CRRES.[13]

AFGL's Roles in the CRRES/SPACERAD Program

During 1982 AFGL worked in a number of ways to assist in the consolidation of the CRRES/SPACERAD program. The new Director of the Space Physics Division, Rita Sagalyn, was prepared to devote extensive in-house resources to realizing the SPACERAD experiments. In March 1982 she appointed Edward G. (Gary) Mullen as SPACERAD Program Manager. The Space Particle Environment Branch, of which he was the Chief, increasingly concentrated its efforts on this program, and the Space Plasmas and Fields Branch under William J. Burke, Jr. provided considerable support. Gary Mullen also became the chairman of the new CRRES Microelectronics Working Group. He immediately went "on the road" in the spring of 1982 to industry and other laboratories to negotiate both participation and funding for the SPACERAD engineering experiments. This activity continued on into early 1983. As part of this effort, he was responsible for drafting the proposal for the SPACERAD Experiment and Test Program discussed above.[14]

The CRRES/SPACERAD program enjoyed the full support of AFGL's then Commander, Colonel John Friel, who made efforts for it to have appropriate visibility. In early 1983 he arranged for CRRES and SPACERAD to be briefed to AFGL's new headquarters in the AFSC chain of command, the Air Force Space Technology Center created in October 1982. Rita Sagalyn continued her personal advocacy for the CRRES Program at higher levels in the Air Force and DoD. By the middle of 1983 its funding, structure, and schedule were well laid-out. On 10 May 1983 the Air Force Space Test Program Office had approved a Space Flight Plan for the SPACERAD Program on board the CRRES satellite, which gave the final official confirmation of AFGL's inclusion in the CRRES mission. At this time the date for the Shuttle launch of the satellite was set for July 1986.

As the SPACERAD program progressed, AFGL continued to play a number of roles in it, ranging from a participating experimenter to a technical and managerial coordinator. These diverse activities developed largely because the SPACERAD Program had grown out of AFGL's earlier RADSAT Program. Within the DoD segment of the CRRES mission, the technical coordination of the SPACERAD experiment package rested with AFGL under Gary Mullen, who reported up to the general management at the AF Space Test Program. The SPACERAD organization itself was an interlocking set of groups consisting of sponsoring agencies; device manufacturers who were contributing microelectronic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SANDIA
VHSIC
JPL
NASA
SPACECRAFT RADIATION
TRANSPORT CODES
SEU DEVICE
MODELING
RADIATION GROUND
TEST PROGRAM
DATA MANAGMENT,
REDUCTION AND
ANALYSIS
INSTRUMENT
DEVELOPMENT
TEST, INTEGRATION
AND CHECK OUT
ADVISORY, REVIEW
AND WORKING
TEAMS

components for testing; and advisory, review, and working teams (see the organization diagram, page 12).

For the Laboratory, its role was most clear-cut in the case of the 18 SPACERAD sensors (environmental and engineering) for which it had the responsibility for delivering the completed sets of instrumentation to Ball Aerospace Systems Division for integration onto the CRRES satellite. Eight of these were AFGL sensors, whose design, fabrication, and testing was organized in-house, while the remaining ten were coordinated with the other participating SPACERAD experimenters; the Naval Research Laboratory, the Aerospace Corporation, and the Air Force Weapons Laboratory. Of these, the main engineering experiment in the SPACERAD package, the Microelectronics Package (MEP), was a unique "box," a major undertaking in itself. The preparation of these 18 sensors involved a number of laboratories and many university contractors.

For the broader program of selecting microelectronic components and designing controlled ground-space tests for them, AFGL was involved in a looser and less-defined set of relationships. As chairman of the Microelectronics Working Group, Gary Mullen had several ongoing responsibilities in this area. These included investigating and acquiring sets of components for testing, monitoring the fabrication of the Microelectronics Package, writing semi-annual status reports on the activities of the Working Group, and providing overall technical administration for the ground tests.[15]

Within the larger arena of the whole USAF/NASA CRRES mission, AFGL also came to play a number of roles. One of the major ones was to coordinate the reduction of the future satellite data primarily for the SPACERAD experiments and also for other DoD and NASA experiments on CRRES. In 1985 the Air Force Space Test Program designated the Laboratory as the agency to handle the processing and distribution of the raw scientific data to all the CRRES scientists, both those at AFGL and at the other participating agencies. The Laboratory's Data Systems Branch was brought in to manage this major task. AFGL had already formed a SPACERAD Science Team in the previous year to start planning how to analyze the anticipated data.

These activities entailed an extensive commitment of technical and managerial effort on the part of the SPACERAD team at the Laboratory. By comparison with the NASA organization, AFGL was carrying a large set of responsibilities with a thin layer of management and a relatively small staff.[16] In addition to coordinating the Laboratory's defined tasks, Mr. Mullen as the SPACERAD Program Manager worked to the best of his ability to protect the program's interests within the larger CRRES mission. On the DoD side, he represented the experimenters at the working level in dealing with the upper level of management at the AF Space Test Program. He also endeavored to work closely with the NASA contractor team at Ball Aerospace Systems Division, which had charge of fabricating the CRRES satellite and integrating its payload.

Because of the way that CRRES had emerged, the enterprise was far from ideal from a managerial point of view. Rather than having a structure with single-point responsibility and internal funding, CRRES represented the complicated arrangement of a double set of consortia, each with a different sponsoring agency and sources of funding. Linking the DoD and NASA experiments had made it financially possible for them to be conducted but, at the same time, created cumbersome and sometimes restrictive conditions for realizing their goals. As Mr. Mullen once put it, "We spend a lot of time stepping on each other's toes."[17] There was no well-defined mechanism for parceling out limitations on experiments when they were called for by considerations of cost or of satellite weight and power capacity. Decisions on adjustments had to be hammered out between participants in CRRES experimenters' committees, and sometimes they required negotiations up to and between the upper-level managements of the two sponsoring agencies.

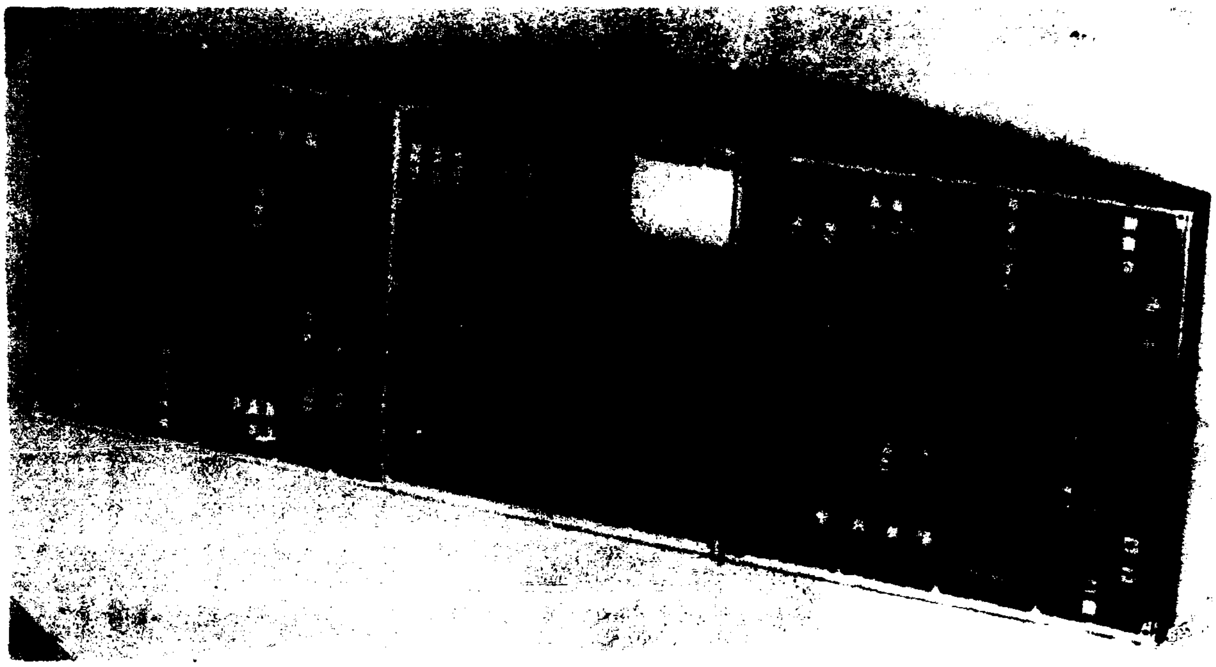
The Microelectronics Package

The engineering experiments in the original RADSAT proposal had consisted of a modestly-sized NASA Components Radiation Effects Measurement (CREM) package, together with dosimeters. In 1983 the CREM package had its name changed to Microelectronics Package (MEP), and between 1983 and 1986 this package underwent a considerable expansion and redefinition of its contents. An Internal Discharge Monitor (IDM) was added to record possible instances of electrical charging by devices housed in the MEP. This instrument, together with a dosimeter and a MOS dosimeter, completed the group of the four SPACERAD engineering experiments.

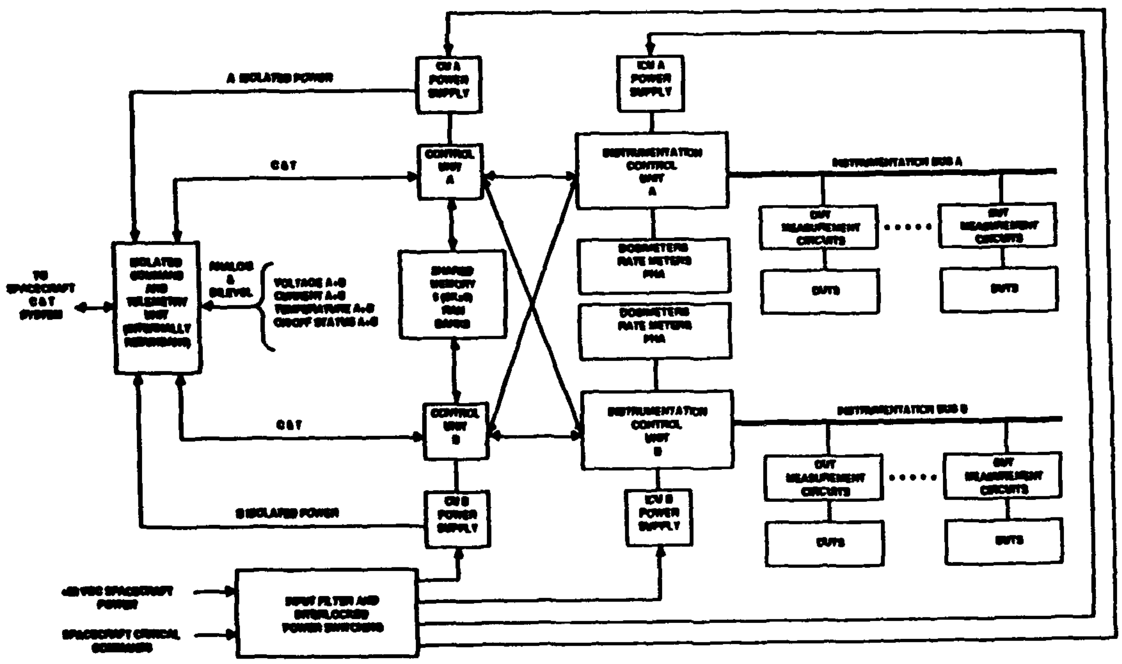
The initial specifications for the MEP were laid out in the overall plan for the SPACERAD Program. They called for a box with a 12" x 15" face for exposure of components, control and support electronics, and the experiment electronics. It was to weigh 50 lbs. and would require 50 watts of power.[18] The vehicle for developing the MEP was an agreement with the Naval Research Laboratory, whose scientists then drew on the contractual expertise used for operational Navy satellites. The NRL prime contractor for the MEP was the Assurance Technology Corporation of Alexandria, VA. ATC's facility in Carlisle, MA, near Hanscom Air Force Base, was to do the actual fabrication of the box, which made it easier for AFGL to monitor its development. The engineer from the Space Particle Environment Branch in the Space Physics Division assigned to the MEP was William B. Huber.

Since calculations indicated that devices located on the inner boards of the MEP would receive a lesser dosage of radiation than anticipated, in May of 1984 the design of the package was altered. The area for direct exposure of components on the satellite's exterior shell radiation was tripled in length, and the weight of the box and the power supply were doubled. Obtaining approval from the Space Test Program for these additional requirements was not easy. The breadboard model of the redesigned package was completed in the summertime, and on 30-31 August 1984 the MEP passed its Critical Design Review, which was held at ATC's facility in Carlisle, MA. In March of 1985 the MEP underwent an independent assessment before fabrication of the flight unit was initiated. Some significant modifications in the design were made as a result of the assessment in order to increase overall system reliability. As a piece of electrical engineering the MEP, in itself, was more complex than many entire operational satellites. It represented experimental hardware of a scope as yet untried, an effort which involved 50-60 engineers at one time or another.[19]

In selecting and acquiring the microelectronic chips and components for testing, the plan was to obtain exact duplicates of chips from the same batch for controlled ground and space testing. The experimental character of many components and devices made for some difficulties in obtaining reliable batches. In a number of cases, initial specimens did not function well and had to be replaced with later, more reliable versions.[20] The rapidly changing state-of-the-art devicesalso necessitated substituting newer products in the MEP. Although the 1985 flight unit boards were designed with symmetrical panels, by the autumn of 1986 these had given way to irregular sections to accommodate the latest selection of devices. These included state-of-the-art silicon devices, VHSIC devices, radiation-hardened devices developed by the Defense Nuclear Agency, gallium arsenide (GaAs) random



The CRRES Microelectronics Package (MEP) with front cover removed



The circuit diagram for the Microelectronic Package on CRRES access memories (RAMs) developed by the Defense Advanced Research Project Agency (DARPA), and specially designed CMOS chips for NASA. The Space Technology Center had also requested the inclusion of a radiation package (RAD-PAK) developed by the Air Force Weapons Laboratory. It was designed to shield individual chips from lower energy electrons, potentially a more cost effective approach than shielding whole electronic systems.[21] For the filled front panel of the MEP as it looked in 1986, see the illustration, page 17.

Procedures for ground testing the selected devices and components were being worked out during fiscal year 1984. The Jet Propulsion Laboratory was the central focal point for the ground-test program, with overall technical administration supplied by AFGL. JPL kept track of all test chips, ground test results, chip specification sheets, etc. The program was to consist of two segments: testing for single event upsets (SEUs) and testing for both total dose and dose rate effects. These tests were to be followed by device modeling in order to arrive at predictive codes for upset phenomena and degradation. The Naval Research Laboratory, Aerospace Corporation, and JPL had responsibility for SEU testing, while the Weapons Laboratory and NASA/Goddard were to handle the total dose and dose rate effects. By the end of fiscal year 1985 the tests for single-event upsets (SEUs) were underway, but testing for total dose radiation had not yet begun. Because of the difficulty of obtaining reliable batches of chips, the testing program was experiencing some delays.[22]

SPACERAD Environmental Sensors

The preparation of the fourteen SPACERAD environmental sensors to measure the radiation belts (see the list on page 19) was a major project for AFGL's

SPACERAD EXPERIMENTS

NUMBER	EXPERIMENT	AGENCY	MEASUREMENT
701-A	MICROELECTRONICS PACKAGE	NRL/ATC/FTS/TELENETICS	MICROELECTRONICS CHARACTERISTICS
701-1B	INTERNAL DISCHARGE MONITOR	AFWL/JPL	DEEP DIELECTRIC CHARGING DISCHARGES
701-2	DOSIMETER	AFGL/PANAMETRICS	TOTAL DOSE/NUCLEAR STARS
701-3	MOS DOSIMETER	NRL	TOTAL DOSE
701-4	HIGH ENERGY ELECTRON SPECTR.	AFGL/PANAMETRICS	ELECTRONS 1 TO 10 MEV
701-5A	MED. ENERGY ELECTRON SPECTR.	AEROSPACE	ELECTRONS 30 KEV TO 2 MEV
701-5B	MEDIUM ENERGY ELECTRON/ PROTON SPECTROMETER	AEROSPACE/MAX PLANCK	ELECTRONS 20 TO 250 KEV PROTONS 40 KEV TO 2 MEV
701-6	LOW ENERGY PLASMA ANALYZER	AFGL/EMMANUEL/MULLARD	ELECTRONS 10 EV TO 30 KEV PROTONS 10 EV TO 30 KEV
701-7A	RANGE TELESCOPE	AEROSPACE	PROTONS 50 TO >600 MEV
701-7B	PROTON SWITCHES	AEROSPACE	PROTONS 20 TO 80 MEV
701-8&9	PROTON TELESCOPE	AFGL/EMMANUEL/MIT	PROTONS 1 TO 100 MEV
701-11A	MAGNETOSPHERIC ION COMPOSITION SPECTROMETER	AEROSPACE/MAX PLANCK	IONS 30 TO 300 KEV/Q
701-11B	LOW ENERGY MAGNETOSPHERIC ION COMPOSITION SPECTROMETER	AEROSPACE/LASL	IONS 40 EV TO 40 KEV/Q
701-11C	HEAVY ION TELESCOPE	AEROSPACE/LASL	IONS 100 KEV TO 15 MEV/NUC
701-13A	FLUXGATE MAGNETOMETER	AFGL/SCHONSTEDT	DC TO 10 HZ MAG FIELD
701-13B	SEARCH COIL MAGNETOMETER	AFGL/UNIVERSITY OF IOWA	5.6 HZ TO 10 KHZ MAG FIELD
701-14	THERMAL PLASMA PROBE	AFGL/UCAL, BERKELEY/ANALYTX/ REGIS COLLEGE	THERMAL PLASMA TO 10 EV E-FIELD DC TO 1 KHZ
701-15	PASSIVE PLASMA SOUNDER	AFGL/UNIVERSITY OF IOWA	E-FIELD 5.6 HZ TO 400 KHZ

Space Physics Division. The specifications for these instruments had been laid out in some detail in the original 1981 RADSAT plan. Subsequently, however, there was further adjustment and elaboration of the particle detectors,the development of a new Low Energy Plasma Analyzer (LEPA), and the addition of a search coil magnetometer. While all the SPACERAD experiments were under the general management of AFGL, the technical preparation of the Aerospace particle detectors (AFGL 701-5, 7, and 11) was handled by the Aerospace Corporation. The preparation of AFGL's particle detectors (AFGL 701-4, 6, 8, 9) was under the charge of David Hardy of the Space Particle Environment Branch, while the wave, field, and plasma sensors (AFGL 701-13, 14, 15) were under William Sullivan of the Space Plasmas and Fields Branch.

The AFGL SPACERAD sensors combined both standard and experimental features. In general, the environmental sensors themselves -- the particle detectors and the field and wave sensors -- represented well-established technology, but their control electronics embodied major advances in this area over the last decade. Two of the particle detectors were intended to be large steps forward in the state-of-the-art. In the case of AFGL 701-4, the high energy Electron Spectrometer, the instrument design was made more complex so that it would reliably record higher-energy electrons (5-10 meV) in the outer radiation belts. The Low Energy Plasma Analyzer (AFGL-701-6) was a highly sophisticated, experimental instrument designed to make three-dimensional measurements of particle distributions in the inner magnetosphere. To do this, it utilized electrostatic analyzers in a new spherical geometry, and the sensor's operations were controlled by a microprocessor.[23]

Work on the SPACERAD instruments was well underway in 1983. Sandia Laboratory provided radiation-hardened microelectronics components for some sensors in order to insure a 3 to 5 year orbiting lifetime. By the end of the year breadboard models of most of the instruments had been constructed. The Laboratory also placed an order for a new vacuum chamber in which to conduct testing and calibration of some of the completed instruments. In the course of development from breadboard to flight unit fabrication and testing, unexpected problems surfaced occasionally. One instance, which was resolved through an in-house effort, was a mechanical problem in stabilizing the sensor heads for AFGL 701-8 & 9, the Proton Telescope (PROTEL). The Fluxgate Magnetometer (AFGL 701-13A) was the first instrument to be completed in the fall of 1984. By the fall of 1985 fabrication of flight models was close to completion.[24]

In addition to the SPACERAD instruments, the AF Space Test Program was flying three other DoD-sponsored experiments on CRRES. These were the two geophysical experiments sponsored by the Office of Naval Research, ONR 307 (Low and Medium Energy Ions) and ONR 604 (Heavy Solar Particles). The data collected would be complementary to the SPACERAD data for modeling the radiation belts. The third was the HESP (High Energy Solar Panel) Program (AFAPL-801), an experiment to space-test gallium arsenide solar cells that the Air Force Aero Propulsion Laboratory was conducting for the Air Force Space Technology Center. These parts of the payload were managed independently by their respective institutions.[25]

The SPACERAD Science Team, which was composed of the principal investigators for the 18 SPACERAD instruments together with representatives from the ONR and HESP experiments, had started meeting in 1984. Its first product was a substantial report describing the individual experiments, which was edited by the team's leader, M. Susan Gussenhoven of AFGL's Space Particle Environment Branch. The main work of the team was to lay the ground work for analyzing and modeling the massive amount of environmental data that would be gathered on CRRES. One important aspect of this was to establish a philosophical consensus on the handling of the database. Rather than an "exclusive rights" approach, it was agreed to make the CRRES data base open to all experimenters and to have it as fully utilized as possible. The team worked on developing specifications for software to analyze the data, and on coordinating their efforts with the Microelectronics Working Group. By the beginning of 1986 AFGL was ready to put out a Program Research Development Announcement (PRDA) for the software development.[26]

Progress of the CRRES Program, 1982-1986

Progress in the CRRES Program as a whole was satisfactory. However, the major milestones for completing the mission slipped several months in 1983. The Critical Design Review for the CRRES Program was eventually completed successfully on 16-19 July 1984. Because of difficulties anticipated in meeting the delivery date for a planned launch in July 1986, the Shuttle launch date for CRRES was set back to October 1986.

In 1984 a new issue arose for the SPACERAD Program -- the reliability of the Star-48 rocket booster planned to propel CRRES from low-earth into geosynchronous transfer orbit. The query about its reliability was prompted by two recent failures of the Star-48's PAM-D motors. The Air Force began discussions with NASA to change over to an SSUS-A, the equivalent of a Minuteman third stage, which has a larger motor than the Star-48. The increased booster capability would accommodate extra weight which had accumulated on the CRRES satellite and offer NASA the possibility of performing chemical release experiments at the higher transfer orbit. However, a change of boosters would cause the launch date to slip again. In October 1984 the Air Force and NASA announced an agreement to switch the rocket booster for CRRES from a Star-48 to an SSUS-A. The change would have the advantages mentioned above for both partners in the program. It also meant that, as of October 1984, the launch date for CRRES was slipped to July 1987.[27]

The CRRES Experimenters' Working Group (CEWG) met several times a year after 1982 in order to deal with the nitty-gritty business of apportioning satellite power and telemetry to the various DoD and NASA participants. One issue of importance to AFGL scientists was the deployment of the long booms necessary for plasma sensing by AFGL 701-15, the Passive Plasma Sounder, and electric field and plasma measurements by AFGL 701-14. For successful deployment the satellite had to perform a spinning sequence, which took additional fuel for the thrusters. There was also concern that the booms might become entangled with NASA's chemical release canisters, and preventive measures were suggested.[28] The question of possible contamination of SPACERAD experiments for the transfer orbit by chemical releases during the low-earth orbit also arose. This issue led to a study, which concluded that contamination would not be a problem.

Another area for discussion was the funding and arrangements for creating data tapes for each participating agency. Since AFGL was to be the processor and distributor of the raw data tapes from the satellite, staff members from its Data Systems Branch worked on setting up a CRRES Data Management Plan. The focal point for this substantial project was Robert McInerney. In June 1985 AFGL reached agreement with the Space Test Program on funding and respective responsibilities for this task. The handling of CRRES data presumed storage capacity beyond current capability of the Laboratory's computation facilities. To meet the need, in the spring of 1985 AFGL proposed to add on-line mass storage

SPACERAD team members at Ball Aerospace, Boulder, CO, 21-24 January 1987. Left to right: Al Stevenson (JPL), Bill Huber (AFGL), Dan Odem (U Iowa), Mike Smiddy (AFGL), Peter Anderson (BU), and John Wygant (UCal/Berkeley).

to its facilities, and its Information Systems Management Division started work on the acquisition process.[29]

Impact of the Challenger Disaster

Towards the end of 1985, the pace of work at AFGL intensified to meet a tight fabrication schedule for several instruments. The schedule at this time called for delivery of the payload to Ball Aerospace in August 1986. Of the 18 SPACERAD experiments about half were built, and the others were in the process of fabrication. The mood of concentration in the SPACERAD team was shattered at the end of January 1986 by the loss of the Shuttle Challenger. It had a great emotional impact, both because of the human tragedy and because it signified a dramatic reversal of the optimistic hopes with which the first Shuttle had been launched less than a decade earlier.

Events following the loss of the Challenger had a major impact on a broad range of Laboratory programs.[30] Most immediately, the loss of one out of four Space Shuttles and the subsequent decision by NASA to redesign the boosters before resuming flights meant a substantial delay for payloads planned to ride on the Shuttle. At this point in time, unfortunately, AFGL had several large payloads scheduled for Shuttle flight. The CIRRIS 1A experiment for infrared background measurements had completed integration for a launch in March of 1986, and CRRES/SPACERAD was to fly in July 1987. These two programs represented a major investment of exploratory development resources by the Infrared Technology and the Space Physics Divisions over the last decade.

As the SPACERAD Program Manager commented later, the grounding of the Shuttle fleet was "the worst thing that could have happened to the program."[31]

The implications of a delay in launching the CRRES satellite were serious. Because of the rapid development of electronic devices, a delay in the CRRES mission would mean that the chips and components being tested for DoD and NASA as well as some of the environmental sensors would not be the latest state-of-the-art technology by the time of the launch. CRRES data on radiation effects would be slower to reach agencies in charge of redesigning Air Force space systems. Since changes in the design of these systems (so-called "block changes") are made every five or six years, implementation of improvements in radiation-hardening might be deferred for a number of years. DoD satellite systems operating from geosynchronous down to low-altitude orbits could lose timely support.

Despite the postponement of the CRRES launch date, work towards the delivery of the SPACERAD instruments to Ball Aerospace for integration was not interrupted. The Air Force Space Test Program agreed to continue funding for the CRRES satellite and to help look for another launch opportunity. After the integration and testing of the experiments on CRRES, it was planned to do any necessary reworking of the sensors and then to store both them and the satellite until a new launch date was set. In mid-August 1986 AFGL delivered the plasma and fields instrumentation to Ball Aerospace and then, two weeks later, four of the particle detectors. By the end of the year the integrating contractor had received all 18 SPACERAD experiments, including the Microelectronics Package with its complement of devices. (For a complete list of the devices selected for testing as of the end of 1986 see Appendix B.) The instruments were packaged in 34 boxes for spaceflight. Each experiment had been previously tested and calibrated individually, and some had also been cross-calibrated. All of them were now bolted onto the CRRES satellite for testing.[32]

The delivery of the SPACERAD instruments for integration at Ball

Aerospace was a major milestone for AFGL, marking the culmination of more than four years' work by the Space Physics Division. The SPACERAD payload represented an investment by its sponsors of about $20 million, half of this for the Microelectronics Package and half for the environmental sensors. Because of the scope and complexity of the project, this completion was a highly significant accomplishment from both a technical and a managerial point of view. By the time the integration and testing at Ball were completed in 1987, the Space Physics Division had committed about 50 man-years of intensive effort and nearly $10 million in exploratory development funds to SPACERAD.[33]

Early in 1987 the CRRES satellite, with its Air Force and NASA payloads, began the system testing at Ball Aerospace. Because of the awareness that CRRES would have to be stored and then retested before a launch, there was disagreement about the extent of testing needed. Because funds were low at this point, the Laboratory urged Ball Aerospace and NASA to save funding and work effort for the time when CRRES would be retested. By the summer of 1987 the AFGL instruments had been returned to the Laboratory. The AFGL dosimeter and the Low Energy Plasma Analyzer were put in storage while AFGL 701-6 and AFGL 701-8-9 were being given some final reworking. Although the ground-testing program had progressed through most of 1986, the delay in the launch resulted in the loss of some outside funding for fiscal year 1987 and beyond. The SEU device modelling was stopped at this point and the entire test program cut back.[34]

Reconfiguration of the CRRES Mission, 1987-1988

The urgency for timeliness in the SPACERAD Program led AFGL's Space Physics Division to press for the earliest possible flight assignment on the new launch manifest that NASA was to publish for the remaining three Shuttles. At the same time the Division Director, Rita Sagalyn, also explored the possibility of flying selected SPACERAD experiments on other satellites of opportunity. Early in October 1986 NASA published the new Space Shuttle payload manifest. Based on the assumption that flights would be resumed in February 1988, it set up a schedule for specific flights between 1988 and mid-1991, followed by more general listings by time-period out into the mid-1990s. In this schedule CRRES was designated for a 1992-93 flight.

This date, which was by no means firm in itself, was unacceptably late for AFGL. As Rita Sagalyn informed the Director of the Space Test Program, AFGL did not plan to support its program for a single, comprehensive, measurement payload if the launch would be delayed beyond the 1989 time frame.[35] If there were a delay of two to three years, the instruments could be adjusted in order to maintain their applicability to Air Force mission goals at the time of launch. Management of a delayed launch would not be easy. In view of the large aggregate of sponsors, technical contributors, and contractors for CRRES, it would be difficult to sustain the team over an extended waiting time. There were also the "standing army" costs that AFGL would incur for a strung-out program. Because of the launch postponement, the outside funding for SPACERAD had been cut in fiscal year 1986. Some money did become available again in fiscal year 1987.

If the delay in launch extended into the early 1990s, technical considerations militated against continuing the SPACERAD Program in its present form. By then some of the environmental sensors would embody outmoded technology and would no longer represent an investment worth holding onto. It would make more sense at that point to utilize the advances made and experience gained in developing the SPACERAD instruments to start work on a new generation of sensors.[36]

During the summer of 1987 the future of the CRRES Program remained a question mark. AFGL was continuing to negotiate with the Air Force and NASA to obtain an early launch for CRRES, either on the Shuttle or on an expendable launch vehicle. One possibility under discussion was to incorporate CRRES into a multi-satellite program sponsored by NASA, the Global Geospace Science (GGS) Program, which was formerly called the OPEN (Origin of Plasmas in the Earth's Neighborhood) Program. CRRES would replace some of the functions of the GGS EQUATOR satellite which was dropped by NASA due to funding cuts. However, this would require some reconfiguration of the payload and new NASA funding in fiscal year 1988 to cover the cost of an Atlas-Centaur booster.

By the autumn of 1987 this alternative opportunity for launch had materialized. CRRES was to serve as the first-to-fly segment of the NASA GGS program, while maintaining its original Air Force mission. The Air Force and NASA gave Ball Aerospace, the contractor in charge of the CRRES satellite, the go-ahead to work on plans to modify the satellite for launch on an Atlas/Centaur booster. On 11-15 July 1988 there was a Delta Critical Design Review (CDR) for the reconfigured satellite. Whereas CRRES had originally been a Shuttle-launched mission with a two-phase orbit, low-earth orbit (LEO) and then geosynchronous transfer orbit (GTO), it was now reconstituted as a rocket-launched, single-orbit (GTO) mission.

As a result of this change, there was no elimination of either of the major components of the mission -- radiation effects or chemical releases. However, compromises in the goals of each component had to be effected because of greater weight, power, and size restrictions in the reconfiguration. For reasons of weight, the Orbit Transfer Stage (OTS) was eliminated, a single GTO mission formulated, and the number of canisters for NASA's chemical releases was halved from 48 to 24.

The chemical releases previously planned for low-earth orbit were subsequently transferred to sounding rocket vehicles.

The timing of the GTO orbit previously planned for the SPACERAD studies was adjusted to increase the opportunities for NASA chemical releases at the perigee. DoD's accompanying LASSII (Low-Altitude Satellite Studies of Ionospheric Irregularities) experiment (NRL-701) was also accommodated. Because of telemetry restrictions, the Delta CDR included a plan to alternate data-taking at perigee between LASSII and the SPACERAD field and wave experiments. To meet the 14 ft. diameter limit of the rocket-fairing envelope, the solar panels were rearranged in a more compact configuration. The positive aspects of the planned Atlas/Centaur launch were that it would permit battery reconditioning a few days before launch, monitoring of the payload up to the last seconds, and separation from the booster with its Command Storage Memory (CSM) already loaded for activation.[37]

The Critical Design Review laid out a schedule for CRRES instrument delivery in the spring of 1989 with a launch date set for June 1990 at Kennedy Space Center, FL. The flight designation for CRRES continued to be P86-1. Purchasing of an Atlas/Centaur rocket from General Dynamics was NASA's responsibility. By the autumn of 1988, NASA/Lewis had sent a letter contract to General Dynamics for the Atlas/Centaur launch vehicle. The vehicle for CRRES was to be the first in a new series of rockets that General Dynamics would make for the commercial market. In an unusual payment-in-kind arrangement, NASA/Lewis traded about $65 million worth of surplus Atlas hardware and tooling to General Dynamics in exchange for the launch vehicle. The AF Space Test Program (as quoted in the press) had spent $170 million in buying the CRRES satellite from Ball Aerospace, developing its operating software, and preparing to interpret its data.[38]

In this whole set of negotiations, both the Air Force and NASA had shown flexibility and accepted compromises in programmatic objectives in order to move on with the CRRES mission. Thus, by the end of 1988 it had been salvaged from what could have been death by delay and was now scheduled for a new launch date in 1990. For the SPACERAD segment of the program, AFGL made a commitment to a renewed major effort. Between the reconfiguration and the launch, the Space Physics Division continued to devote extensive manpower and resources to CRRES. However, the delay did have some negative effects for the SPACERAD engineering experiments. The funds from various sponsoring agencies had halted in 1986, revived somewhat in 1987, but then dwindled away in 1988. As a result, the ground-testing program for the microelectronic components came to an end, but some predictions for the occurrence of SEUs and the failure rates of components in space were in hand by the time of the CRRES launch.[39]

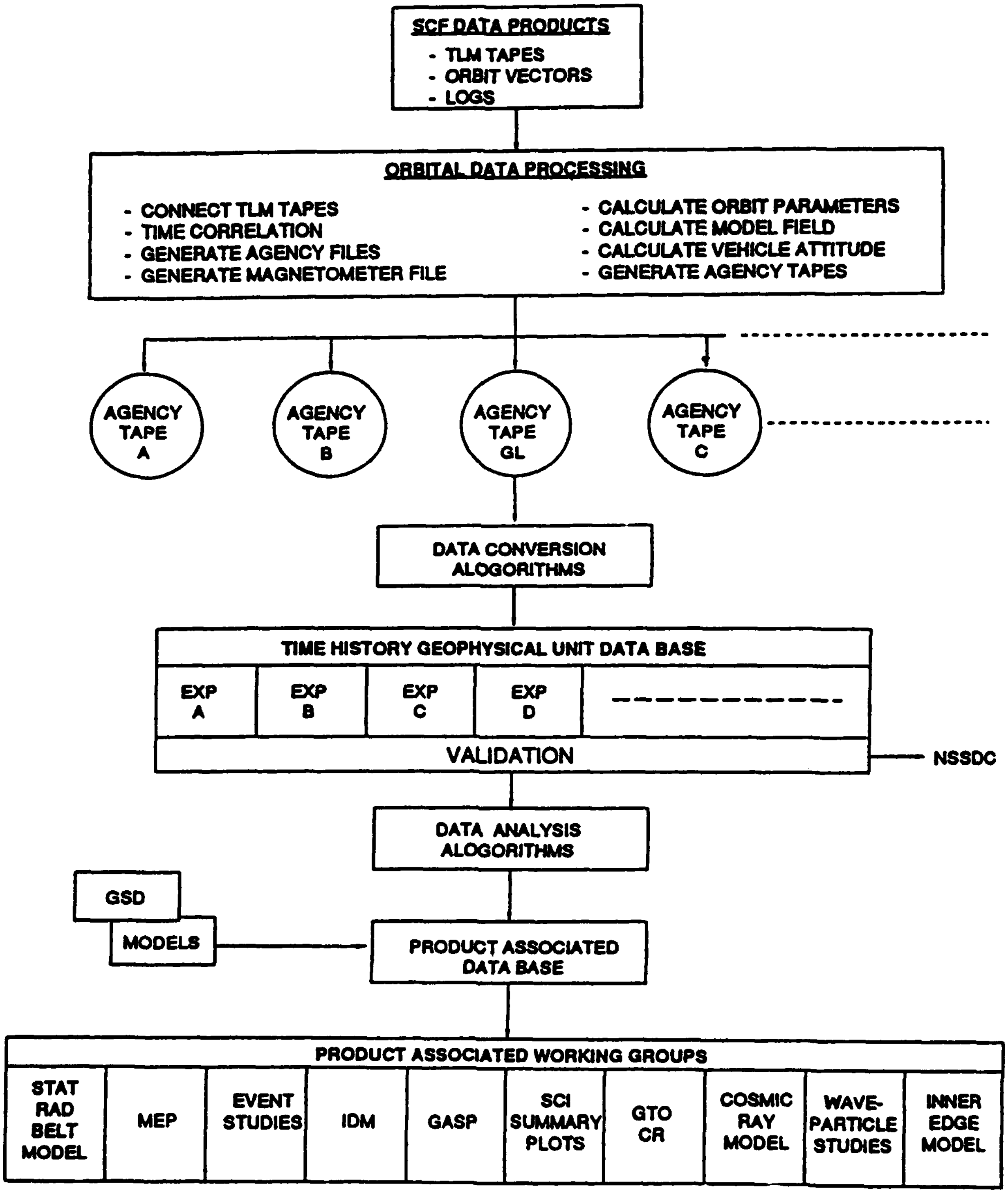
Plans for CRRES Data Reduction and Analysis

With the CRRES satellite reconfigured and a launch date set, planning at AFGL for processing the CRRES data gathered momentum. In the autumn of 1985 the Laboratory had signed a Memorandum of Agreement with the Space Test Program. AFGL would be sent the raw telemetry stream from CRRES (in analog form) recorded at the Air Force's Satellite Control Facility (SCF), recently renamed the Consolidated Space Test Center (CSTC), in Sunnyvale, CA. From this it would then generate digitized, computer-compatible data tapes. The Laboratory would be responsible for creating tapes for all the agencies that had experiments on CRRES, a total of 13 agencies representing 30 experiments.[40] Under the terms of the MOA, STP would provide funding for AFGL to cover the generation of tapes for the first year after launch. Funding for processing of the data anticipated from a subsequent two-to-four years on orbit had yet to be arranged but presumably, once the satellite was orbiting successfully, it would be contributed by the participating agencies.

For the Laboratory's Data Systems Branch to handle this assignment, on-line computer storage for the mainframe Cyber had to be greatly expanded. This involved both a reworking of software and the purchase of state-of-the-art hardware. To handle the CRRES data stream, the plan was to purchase a machine with 55 gigabyte capacity and the possibility for expansion to twice that amount. Between 1986 and 1989 the acquisition of the mass storage equipment had gone through many vicissitudes. After an initial failure to purchase the equipment due to procurement difficulties, the project was shelved with the postponement of the CRRES launch in the aftermath of the Challenger disaster. In 1988, with the mission revived, efforts to procure central site storage were resumed, this time with success. By the end of FY-89 arrangements for purchase of the on-line mass storage were almost completed. The contract was awarded to Masstor on 14 October 1989. Since the equipment was to come with a double-density reader, it effectively increased the capacity of the hardware to 110 gigabytes. Work on the networking software was to follow in FY-90.

As the CRRES Program evolved, the arrangements for the production of the agency tapes had been modified, although the original 1985 Memorandum for Agreement with the Air Force Space Test Program was not rewritten. The delivery schedule for the agency tapes was set up as follows: two-to-four weeks after AFGL received the original analog tapes from CSTC, it would start shipping the digitized raw data tapes in weekly installments for the 13 agencies with experiments on CRRES. The Data Systems Branch was to supply an extensive ephemeris package for defining coordinate systems and mapping the data. In the summer of 1989 staff

CRRES DATA FLOW



from AFGL's Data Systems Branch went out to Ball Aerospace Systems Division and recorded and digitized readings from the CRRES instruments to test its processing software. The next month a technical memorandum was issued with the definitive program for generating the agency tapes.[41]

The whole process of CRRES data reduction and the products to be developed were laid out (see the flow chart on page 33). After raw, digitized data on the agency tapes was converted into geophysical units, a validated Time History Data Base (THDB) would be created for each of the 30 CRRES experiments. This work was to be done by Boston College under contract to the Data Systems Branch. The Branch also set up contracts to provide scientists with some of the additional software packages to be attached to the THDBs. These were a) an ephemeris file of 48 elements, b) a magnetometer file of 8-second averages of each vector component, and c) a satellite attitude file. In addition, algorithms for determining particle pitch angle from detector look directions, coordinate transformations, magnetic field line tracing from a variety of magnetic models, and calculation of particle adiabatic invariants were developed to be made available on request. Gary Mullen, the program manager for AFGL's experiments on CRRES, planned to maintain a set of the Time History Data Bases, possibly on optical disks, for the Laboratory's own use. During 1989 discussions were underway between the Laboratory and NASA about archiving this data base at their National Space Data Center (NSDC) where it would be accessible to researchers on a long-term basis. By the time of the launch, however, an agreement had not been reached.[42]

In order to plan for the scientific analysis of the reduced data, the principal investigators from the SPACERAD and other DoD experiments and their supporting contractors had formed a SPACERAD Science Team. Its activities were being coordinated by M. Susan Gussenhoven from AFGL's Space Particle

Environment Branch. The Team met, starting in 1984, to formulate the general philosophy for the CRRES data and to determine the scope of the data analysis and software needed. With the grounding of the Shuttle fleet, this work was suspended. The Team resumed its activities in 1988. AFGL sent out a Program Research Development Announcement (PRDA) for data analysis, and then the contracts were awarded.

On 6-7 March 1990 the Science Team held a major working session at S-Cubed, San Diego, CA, to plan the shape of the data bases which were to be the source of the main models and studies that would be the final products of the CRRES Program.[43] (These products are listed on the bottom line of the flow chart.) There would be three data bases created for engineering studies: one to support analysis of the Microelectronic Package (MEP), another to support analysis of the Internal Discharge Monitor (IDM), and one to support the analysis of the gallium arsenside solar panel (HESP). In terms of modeling the radiation belts, there was to be a statistical data base which would improve the existing Static Radiation Belt Model. This would be combined with an "event" data base (case studies of geomagnetic storms and other major solar-induced disturbances), together with generic high-energy particle studies, to create the data base for new dynamic models of the belts. The CRRES mission would also yield a data base on cosmic rays, which would be used to upgrade existing models.

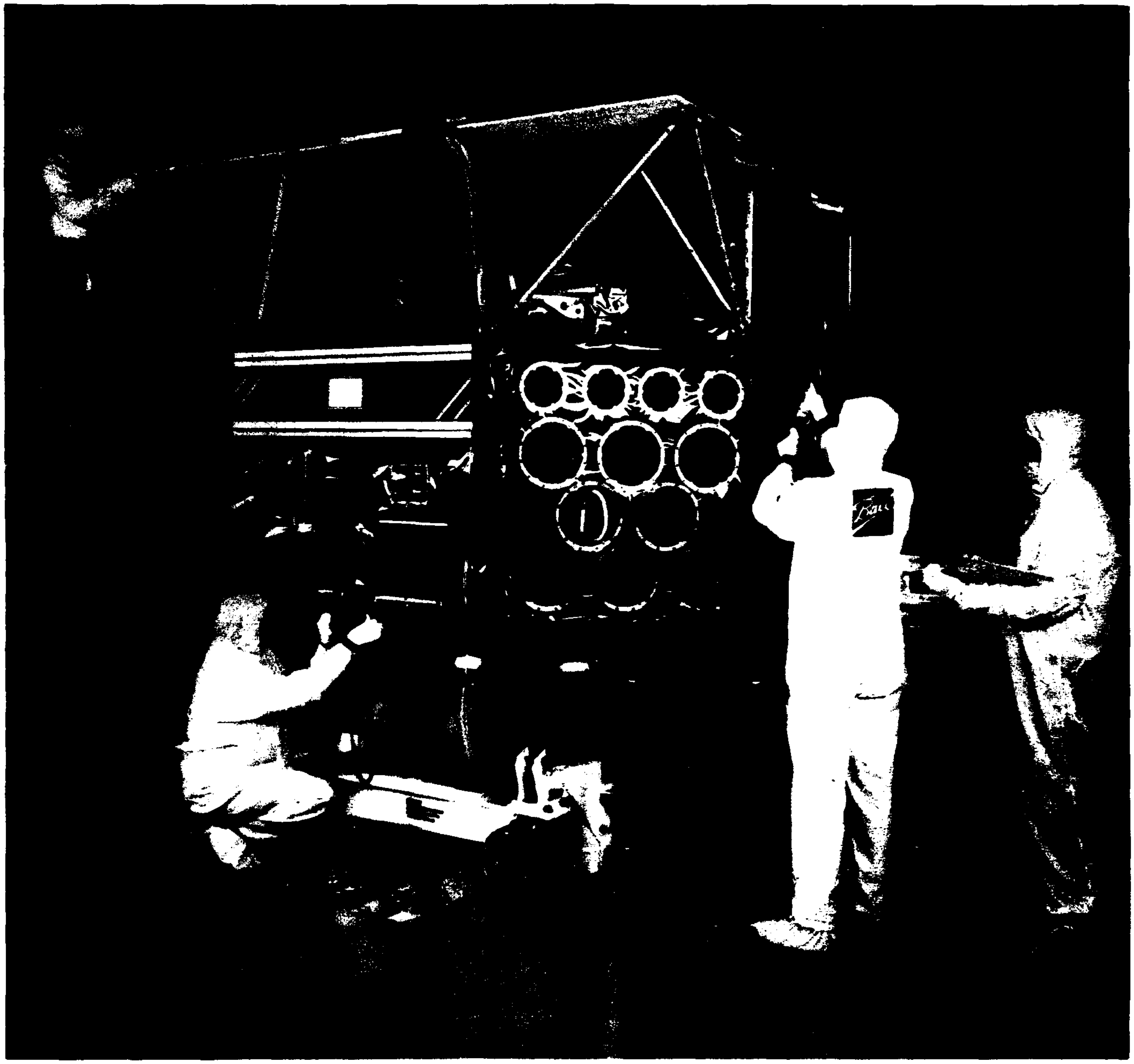
The new date of the CRRES launch placed it on the downside of solar maximum, which statistically is a good time for observing "events." If the launch was successful and the instruments functioned well, scientists could expect a flood of new data. It was hoped that the sensors and the satellite would hold up for at least three to five years. AFGL scientists were preparing to apply to CRRES the expertise in creating detailed statistical models that they had developed in the earlier Satellite

Charging at High Altitudes (SCATHA) Program and in studying data from space sensors on the Defense Meteorological Satellite Program (DMSP).[44] CRRES data would be utilized to arrive at more accurate specification of average conditions in the radiation belts and the probabilities of exceeding these by a certain level. Low-altitude studies had suggested that the radiation danger to microelectronics and astronauts had been overestimated. If the CRRES data validated this point of view, it would be possible to lower the standards safely.

There were a number of specific questions to which scientists hoped CRRES would provide the answers. The data from the DMSP satellites in the mid-1980s, when analyzed, had provided evidence for the dynamics of the radiation belts during solar minimum. From CRRES it was hoped to gain complementary insights for solar maximum conditions. One question of interest was whether the inner proton belt is stable even in big storms. The DMSP data showed the formation of a second, fairly long-lasting belt following the large magnetic storm of February 1986. Other questions to explore were what drives the high variability of the outer zone electrons and what role ions play in driving pitch angle and radial diffusion from the outer belts inward. Additionally, the magnetometer and ion data should contribute to better ring current models for improving magnetic field models.[45]

System Testing of the CRRES Satellite

The setting of a new launch date for the CRRES mission in June 1990 backfilled the intervening time with a schedule for redelivery of the instruments and a second round of system testing for the reconfigured satellite. The satellite testing at Ball began in August 1989 with functional performance, electromagnetic compatibility and thermal testing over the next several months. During this period



Technicians at Ball Bros. check out the reconfigured CRRES satellite during system testing at the end of 1989. The left-facing panel on the satellite houses the Microelectronics Package (top panel). Underneath it, on the left, the LEPA sensor; on the right, the Space Radiation Dosimeter. The Internal Discharge Monitor is in the lower right-hand corner. The right-facing panel contains the canisters for some of the NASA Chemical Releases.

Gary Mullen and the SPACERAD team of scientists first had to prepare the instruments for redelivery, which involved reassembling and then calibrating them. The AFGL particle detectors had been stored under special conditions, in a purged environment with dry nitrogen. The Low Energy Plasma Analyzer (LEPA) developed some electrical problems as the result of increased energy levels. Its supporting ceramic plate was too thin for the higher voltages and caused sparks, so that it had to be redesigned. A latch-up error due to noise from the power source was also corrected. For the Microelectronics Package, the MEP Working Group had decided in July 1988 to add a new component for testing, an IDT RAM. When the Group met again in the fall of 1989, it considered, but decided not to include, Silicon-on-Indium (SOI) chips for testing. Thus the list of chips and components remained almost identical to what it had been in late 1986. AFGL delivered the SPACERAD instruments (including the Microelectronics Package) to Ball Aerospace in May and June 1989.[46]

During the second round of system testing for the reconfigured CRRES satellite, the thermal vacuum testing in October 1989 turned up a major issue for the long-term viability of the mission. Ball's thermal model for maintaining the satellite within the thermal operating limits for the SPACERAD instruments had not included the effects of either the presence of NASA's chemical canisters or the holes that would be left after their ejection. In the first instance, the concern was with overheating; in the second (and more worrisome) instance, the concern was with the expected increase in the loss of operating capability due to heat leakage. Because of the latter, AFGL requested a repeat of the thermal balance test of the satellite, with and without the canisters, and a review of Ball's thermal model. To stress the urgency of the issue, Col Robert J. Hovde, AFGL's Commander, raised it in a personal letter to Col John E. Armstrong, Director of the Air Force Space

Test Program. Technical advice from the Aerospace Corporation, together with Ball's estimates of extra expense and delay that would be incurred in the program, led to a rejection of the Laboratory's request. However, the Space Test Program supported a compromise proposal to add thermal blanket flappers over the canister holes and to perform a subsystem thermal balance test on them to check their effectiveness. Colonel Armstrong expressed confidence that this approach would enable CRRES to achieve at least a three-year mission goal. [47]

Another satellite issue that emerged was the adequacy of the electrical power supply. The wiring size was too small for the 15 amps of power used by the spacecraft. The problem was detected in a voltage drop to the Internal Discharge Monitor (IDM) at the end of 1989, although it was applicable to the whole spacecraft. Some, but not all, wires were replaced to reduce power loss in the wiring harness itself. The period of testing was completed by March 1991. On the nineteenth of the month the CRRES spacecraft was shipped from Ball's plant in Colorado overland to Cape Canaveral, where it arrived on 23 March. The last functional tests on the instruments were conducted between 16-20 April. They revealed no problems with the instruments themselves, although there were some difficulties in sending commands from the spacecraft to the sensors. Then the satellite instrument bus was turned off until launch time.[48]

The CRRES Launch and Turn-On of the Instruments

While the system testing was in progress, preparations for the launch were getting underway. The CRRES Experimenters' Working Group (CEWG), now retitled the Flight Operations Working Group (FOWG), began to meet again as of fiscal year 1989 to plan procedures for operations on orbit. By the spring of 1990, with system testing completed and planning for data reduction and satellite operations well-underway, the focus of the program turned to the launch itself. In February 1990 the official launch date for CRRES had been set for June 7, but this date started to slip during launch preparations.

The SPACERAD team focused its attention on the more detailed schedule for the launch "windows," i.e., the set of dates and the hours in each day within which the launch could take place. This was an issue in which the differing experimental goals of the DoD and NASA segments of the mission came to the fore. For the NASA experimenters, the main goal was to obtain a launch time which would best position the satellite for chemical releases. Three kinds of chemical releases were planned. First, there were releases at the dawn terminator, highest latitude (18°) inclination, over the Arecibo facility in the spring. Secondly, there were releases near perigee at dusk over the Indian Ocean, and thirdly, there were high-altitude releases, near midnight at apogee, over North America in the winter. The requirements for the dawn releases were the most stringent.

For the SPACERAD experimenters, the most important requirement for data-taking was to have the maximum exposure of the satellite's solar arrays to the sun. In order to keep the sensors functioning, it was necessary to have no more than 90 minute "eclipses," i.e. times when the satellite was in the earth's shadow. If the time was longer, solar power to the batteries would not be sufficient to keep the instruments going, and they would have to revert to duty cycling. Another important consideration was the position of the satellite vis-a-vis the radiation belts. In order to be assured of getting data, SPACERAD experimenters wanted to have CRRES go through the magnetospheric tail region with apogee near midnight at an early stage of the mission. For the best coverage, it was desirable to have the satellite traverse the belts as close as possible to the magnetic equator, with a minimum inclination in the orbit. The schedule that NASA issued at the end of May 1990 for the daily launch "windows" in July and early August was geared primarily to meet the conditions for the dawn chemical releases. For the SPACERAD experimenters this resulted in an undesirably large number of 100-minute "eclipse" periods. Although Mr. Mullen made efforts through the Air Force chain of command to have the schedule modified, this did not prove to be possible.[49]

When the General Dynamics booster for CRRES underwent "wet tests" at the end of May, an accident occurred which set the launch date back into July. One of the cooling lines with helium broke loose and banged around the payload, necessitating repairs and component replacements. It was hoped to complete repairs in 10 days and then redo the test on 19 June. At this point, the official launch date was reset for 9 July. The repair work was followed by the mating of the satellite and the booster and then flight simulations and rehearsals. A further delay was incurred by problems with the handoff from the ground launch control software to the onboard control software during a simulated countdown. This required a second countdown dress rehearsal on 26 June. By the end of the month, CRRES was standing on Pad 36-B at Kennedy Space Center, FL, with the launch date now set at 17 July. This launch date was scrubbed in turn because early in July there were problems with one of the decoders on the satellite.[50]

These additional delays added further tensions and complications around the launch. The later that the launch took place, the shorter the daily "window" that met the chemical release requirements became, and so NASA was eager to launch as soon as possible. This delay in the schedule, on the other hand, did not create any problems for SPACERAD requirements. The extra delay also increased the potential for adverse weather to interfere with the launch. Because the Cape

Canaveral area in the summertime is noted for thunderstorms late in the day, the coincidence of the short daily "windows" with this time-period was not auspicious. The threat of lightning posed issues of launch safety which were a major concern to both the Air Force and NASA.[51] A Third SPACERAD-Atlas Science Team Meeting/Microelectronics Working Group had been planned at Cape Canaveral to coincide with the launch. Its purpose was to review the status of the time history, to discuss quality control of the data, and criteria for choosing "events" to study. While the Meeting was eventually held on 20 July, many of the scientists had to leave the Cape for other commitments prior to launch. Only a few core members of the AFGL team, M. Susan Gussenhoven, David Hardy, Howard Singer, Lt Michael Violet, and some others were able to stay on through the launch.

It took several attempts before CRRES was successfully launched on 25 July. During the first attempt on Friday, 20 July, a compressor developed a leak which required a day to repair. On Sunday, 22 July, the launch was postponed because of lightning nearby and high winds aloft, while subsequent efforts on Monday, 23 July, were scrubbed at thirty seconds before launch due to the inability to switch from external to internal power for the booster. On Wednesday, 25 July, various problems emerged during the final countdown, but none were considered critical enough to halt it.[52] At approximately 19:21 Universal Time, the Atlas-Centaur booster with its payload ascended majestically into orbit to the great relief and satisfaction of all the participants in the mission. After a decade of preparations, including a three-year delay due to the grounding of the Shuttle fleet, CRRES was finally launched.

The accomplishment of the launch set the stage for the next major events in the CRRES Program, the turn-on and check-out of the SPACERAD instruments. In order to be in place for these key operations, Gary Mullen had elected to skip the launch at Cape Canaveral and to proceed ahead of time to the Air Force's Consolidated Space Test Center (CSTC) in Sunnyvale, CA. "C-stick," as it is pronounced, was to be the controlling agency for CRRES flight operations and the recording center for the raw telemetry stream from the satellite. Turning-on and checking-out the instruments was a complex process which required about a month to complete. The booms for the field and wave experiments had to be extended in stages, and several of the instruments could not be turned on until the satellite had reached its final spin rate of about 2 rpms. When the checkout process was completed, one set of contracts for the program would terminate and a new set go into effect.

Two weeks after launch, Mr. Mullen reported on the status of the instrument checkouts as of 6 August. The first SPACERAD instruments were turned on less than 24 hours after launch, at approximately 12:50 UT 26 July, during the second orbit. These were the two dosimeters to measure the total radiation dose to the spacecraft and to the microelectronics being tested. Next came the Microelectronics Test Package itself, and then over the following week, high and medium energy particle detectors. On 31 July the Astromast Boom with the magnetometers was deployed. The two sets of 100 meter tip-to-tip long wire booms to measure electric fields, waves, and plasma densities were extended in stages until they reached their maximum extension on 6 August. As of this date, 14 of the 18 SPACERAD experiments had been turned on.

During the following three weeks the CRRES satellite was spun down from 15 to 2 rpm and then the remaining four SPACERAD instruments were turned on starting with the Low Energy Plasma Analyzer (LEPA). The initialization of the SPACERAD instruments comprising turn-on and a calibration check was officially completed at 1035 UT on 26 August 1991. Overall, the state of the SPACERAD package looked very promising for data-gathering. Because of the complexity of the sensors, however, there were still adjustments to be done to get them into a peak operational condition, and so most of the experimenters made trips to CSTC to do the "fine-tuning."

In the whole battery of SPACERAD environmental sensors, at this point only two had major problems. One was an experiment sponsored by the Aerospace Corporation to measure low-energy ions, which was only functioning nominally. The other sensor in difficulty was the fluxgate magnetometer. Initial scans from the magnetometer indicated that it was out of alignment by about 15 degrees, apparently due either to an improper mounting alignment or a failure of the boom to repeat its original deployment angle. The correct functioning of the magnetometer was important because it provided a measurement of the magnetic field for all the other sensors. It also had the unusual capability to send a real-time signal to the LEPA instrument which enabled LEPA to measure particles better along the direction of the magnetic field. The magnetometer experimenter, Howard Singer, determined that, for the most part, the offset in the alignment could be handled through a modification of analysis and calibration provided the magnetometer was stable in this new orientation. It was later determined that the most likely cause of the incorrect alignment was that the placement of spacecraft thermal blankets snagged a cable and prevented the boom from rewinding the last few degrees.[53]

The check-out period was one of hectic activity for the whole SPACERAD team and also for the staff manning CRRES tracking operations at CSTC. Accustomed to simpler procedures for operational satellites, the staff found the exceptionally demanding. Mr. Mullen worked with CSTC staff to coordinate and smooth flight operations and to establish procedures for handling specific problems.

Among the issues that arose were adjustments of the thermal environment for some instruments, clarification of commands sent on the command-uplink in order to prevent false instructions or unsafe conditions for the instruments, and resetting the spacecraft clock which was skipping milliseconds and causing loss of data. These issues spilled over from the start-up period into the months that followed.

Some problems emerged with the satellite hardware supporting the SPACERAD package which either had immediate effects on experiments or threatened to become problems in the future: a pressure leak in one of the two on-board tape-recorders for the data and overheating in one of the spacecraft's two main batteries.[54] After 100 orbits one of the Interface Control Unit power supplies for the Microelectronics Package failed to function. Due to the problems it was decided to operate with only half of the devices until later in the mission. The test package had redundant architecture. There were two independent, complete sets of test chips in the MEP, each containing multiple samples, so this resulted in no loss of function. However, it did cut the number of devices under test in half, which reduced the statistical significance of the tests.

The three months following the end of the checkout period saw adjustments of sensor operation, further calibrations, and ongoing discussions about structuring the incoming data. After launch the Data Systems Branch had mobilized for the huge job of ongoing data reduction. It sent out the first batch of agency tapes (for orbit #3) to the 13 agencies with experiments on CRRES early in September 1990. Towards the end of October, a workshop presented preliminary results from the SPACERAD experiments to the scientific community, capping this initial period of data-gathering. The Fourth SPACERAD-Atlas Science Team Meeting with the Microelectronics Working Group was held in the AFGL Science Center from the 23-25 October with about 80 scientists in attendance.[55]

The initial period of data-gathering had opened with one minor "event" which was then followed by very quiet conditions. Observations of the behavior of the microelectronics being tested showed that inner belt protons induced many single-event upsets in the chips, while cosmic rays out at apogee induced relatively few. Preliminary plots of fluxes of electrons and protons at varying energy levels showed two interesting features. The average proton fluxes were as would be expected from the NASA radiation models. It remained to be seen whether the CRRES data would support the concept of a second, storm-related proton belt closer to the outer zone which had been observed in the DMSP data from the mid-1980s, and in McIlwain's data from the early 1960s, but which is not in the existing NASA model.[56]

By contrast, the electron fluxes in the outer belt showed a much lower average dose rate over a period of 19 orbits than would be predicted by the NASA model. If this observation continued to hold under varying conditions of geomagnetic activity, it would imply that the NASA electron model needed to be substantially revised. In terms of the practical consequences, as Mr. Mullen observed, it would mean that spacecraft for geosynchronous orbit built to withstand natural, but not nuclear, radiation, i.e. communications satellites, could operate safely with a lesser amount of shielding -- good news for the designers of these systems. In terms of scientific understanding, it whetted the appetite for further data to make sense of the source and dynamics of electrons in the outer radiation belts.[57]

Conclusion

By the end of 1990 the CRRES/SPACERAD Program had been in progress for nearly ten years and had both evolved and undergone many trials. The original scientific goal of the program, a very ambitious one, was to achieve comprehensive, simultaneous measurements of the Earth's radiation belts in order to create the first dynamic models of space radiation. To increase support for this effort, AFGL first combined its experiments with other space experiments planned by the Aerospace Corporation Labs, the Navy, and NASA, creating the RADSAT Program. When its launch opportunity fell through, AFGL then supported broadening the scope of the program to focus on the practical issues of space radiation effects on advanced microelectronics and the development of valid standards for shielding through a controlled testing program.

The resulting SPACERAD Program emerged in 1982 with a group of sponsors in DoD, NASA, industry, and a large consortium of experimenters. At the same time, to meet the huge costs of a satellite and launch, the DoD/SPACERAD Program joined forces with the NASA/Chemical Release Program for a Combined Release/Radiation Effects (CRRES) satellite to be launched from the Space *Shuttle*. This cooperative approach made the programs financially feasible, but it also required trade-offs between DoD and NASA experimenters' scientific goals. For the SPACERAD experiments, it eventually meant compromises on orbit specifications and power allocation, which placed some limitations on data-gathering capability.

A major trauma came to the CRRES Program as it progressed towards its Shuttle launch planned for July 1987. When the Shuttle fleet was grounded early in 1986 following the accident to the Challenger, a lengthy delay in launching seemed likely. However, the Air Force and NASA arranged for a new expendable vehicle, an Atlas-Centaur booster, and the CRRES satellite was reconfigured for a 1990 launch date. Even with a three-year delay, it was still in time for the downside of solar maximum. The satellite was successfully launched on 25 July 1990, and the SPACERAD instruments functioned when they were turned on. Thus, in the end, SPACERAD instruments functioned when they were turned on. Thus, in the end, against considerable odds, the obstacles to realizing CRRES as a functioning satellite in orbit were overcome. The Space Physics Division's extended investment of manpower and in-house exploratory development funds had paid off. Attention now turned to the task of reducing and then interpreting the enormous stream of data coming in from space. After a decade of endeavor AFGL was on the way to realizing its goal of characterizing the Earth's radiation belts.

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SPACERAD team members receive GL Awards. From left to right: Col Robert J. Hovde, GL Commander, David Hardy, Gary Mullen, Don Brautigam, Howard Singer, and M. Susan Gussenhoven.

FOOTNOTES

1. Interview with Rita C. Sagalyn, Director, Space Physics Division, 18 April 88; Information, Edward G. Mullen, SPACERAD Program Manager, to author, 29 December 1987. See also the AFGL Technical Report, AFGL-TR-85-0017, M. S. Gussenhoven, E. G. Mullen, R. C. Sagalyn, Eds., CRRES/SPACERAD Experiment Descriptions, Hanscom Air Force Base, MA, 24 January 1985, pages 13-34.

2. For the Vette models see Sawyer, D.M. and J.I. Vette, "AP-8 Trapped Proton Environment for Solar Maximum and Solar Minimum," NSSDC/WDC-A-R&S 76-06, NASA-GSFC TMS-72605, December 1976. Ways to improve the model are discussed in Vette, J., I. King, W. Chan, and M.J. Teague, "Problems in Modelling the Earth's Trapped Radiation Environment," AFGL-TR-78-0130, ADA059273, 1978.

3. Interview with Paul L. Rothwell, Space Plasmas and Field Branch (PHG), 6 February 1987. See the Handbook of Geophysics and the Space Environment edited by A.S. Jursa, AFGL, 1985, Ch. 5. The Radiation Belts.

4. Interview with Malcolm MacLeod, Space Particle Environment Branch, 12 November 1991.

5. 1981 Revision of the DD Form 1721 for AFGL-701 (RADSAT) submitted to the Space Experiments Support Program; Briefing, *Radiation Satellite*, (RADSAT) Program, presented by Col Richard B. Kehl, Director, Space Testing Program (SD/YLT), 18 August 1981.

6. AFGL-TR-81-0311, R. C. Sagalyn et al, Eds., Proceedings of the AFGL Workshop on the Earth's Radiation Belts: 26-27 January 1981, Hanscom Air Force Base, MA, 21 October 1981.

7. For a discussion of this previous approach see the letter from Robert A. Skrivanek, Chief, Technical Plans Branch, to the Air Force Office of Scientific Research (AFOSR/XO), subj: 6.1 Funding for Space Shuttle Experiments, 13 August 1980.

8. RADSAT Briefings by Rita Sagalyn and David Hardy, Space Physics Division, November 1981.

9. Message, HQ AFSC/SDS/ACB to AFGL/CC/PHG, subj: STP Funding, R 171300Z November 1981; Memo, Col Paul D. Try, Office of the Undersecretary of Defense for Research and Engineering (OUSDRE) to Col Steven M. McElroy, subj: Reduction in Space Test Program (STP) Funding for RADSAT, 9 November 1981; Gen Robert T. Marsh, AFSC/CC to SD/CC, subj: Radiation Satellite (RADSAT) Program, 4 January 1982. Advanced Development Program Plan, Space Hardened Electronics, prepared by Major J. Criscuolo, USAF Space Division/YLXT, 13 January 1982 (Draft).

10. Hans Mark, NASA Deputy Administrator, to Verne Orr, USAF Secretary, subj: Proposed CRRES Mission, 25 April 1982; Maj Gen Forrest S. McCartney, SD/CV, to Dr Herbert Rabin, OASN (RES), Pentagon, 27 December 82.

11. Memorandum of Agreement between Space Test Program (STP), Space Division (SD/YLT), and the Air Force Geophysics Laboratory (AFGL) for the AFGL-701 (Space Radiation) experiment, 7 September 1982.

    Agreement Between Space Test Program and Spacelab Payload Project Office for Implementation of the Combined Release and Radiation Effects Satellite, 25 April 1983.

    Memorandum of Agreement Between the Department of Defense (Air Force) and the National Aeronautics and Space Administration for a Combined NASA and DoD Research and Development Spaceflight.

12. [E. G. Mullen], Proposal for a Space Radiation Effects Experiment and Test Program, [AFGL, December 1982], 36 pages.

13. NASA AO No. OSSA-2-83, 27 May 1983. For the CRRES experiments see the CRRES System Description Handbook, 2 April 1985 (Revision A), NASA/Marshall.

14. AFGL FY-83 History, I, 9; Interview with E. G. Mullen, SPACERAD Program Manager, 8 December 1983 and 15 October 1987.

15. The progress of work undertaken by the Microelectronics Working Group was summarized in a series of 6 semiannual Technical Status Reports issued by E. G. Mullen covering the period between January 1983 and December 1986.

16. Interviews with M. Susan Gussenhoven, Space Particle Environment Branch, 20 June 1990, and with E.G. Mullen, 21 November 1991.

17. Interview with E. G. Mullen, 2 February 1987.

18. See the Proposal cited above, note 9, pages 8-14. Also E. G. Mullen, SPACERAD Microelectronics Test and Modeling Program, Technical Status Report for July 1983 through December 1983, Part I.

19. E. G. Mullen, SPACERAD Microelectronics Test and Modeling Program, Technical Status Report for January-June 1984, Part II; Same Report for July-December 1984, Part II; Item, Space Physics Division Significant Event, 23 September 1983. Interview with Gary Mullen, 5 June 1990.

20. E. G. Mullen, SPACERAD Microelectronics Test and Modeling Program, Technical Status Report for January - June 1985, Parts I and II; Interview with E. G. Mullen, 15 October 1987.

21. AFGL FY-84 History, I, 57-58; Interview cited above, note 15.

22. E. G. Mullen, SPACERAD Program, Technical Status Report for January - June 1985, Attachment on Ground Testing.

23. Interview with David A. Hardy, Space Particle Environment Branch, 29 October 1987.

24. Interview cited above, note 18; AFGL FY-84 History, I, 66-67; AFGL FY-85 History, I, 81.

25. The AFGL SPACERAD Experiments together with the ONR and AFAPL experiments are individually described in the Technical Report cited above, note 1.

26. Interview with M. Susan Gussenhoven, Space Particle Environment Branch, 9 October 1987.

27. Interviews with E. G. Mullen, 6 March 1984, 10 August 1984 and 26 February 1985.

28. William P. Sullivan, Space Plasmas and Fields Branch, to SD/YCC, subj: CRRES 225, AFGL-701-15 D&E, Cylindrical Wire Antenna Deployment Tests, 26 June 1986.

29. Col Joseph D. Morgan, III, AFGL Commander, to SD/YC (Attn Col Fratzke), subj: CRRES Data Management Plan, 11 June 1985; Eunice C. Cronin, Director, Information Systems Management Division, to AFGL Commander, subject: Acquisition Plan for Mass Storage System (MSS), 22 April 1985.

30. For a general discussion of the Challenger disaster's impact on AFGL programs see the AFGL FY-86 History, I, 57-65.

31. Interview with E. G. Mullen, 20 February 1987; Phone conversation with E. G. Mullen, 12 May 1987.

32. Space Physics Division Significant Events, 14 and 27 August, 12 December 1986. For the location of the SPACERAD experiments on the CRRES satellite see the CRRES System Description Handbook, NASA/Marshall, 15 July 1986 (Revision B).

33. Interview cited above, note 15. For the AFGL SPACERAD funding see Appendix A.

34. E. G. Mullen, SPACERAD Microelectronics Test and Modelling Program, Technical Status Report for June-December 1986, Part I; Interview cited above, note 26; E. G. Mullen to SD/CLTP (Attn: Col J. Armstrong), subj: Early Test Completion for CRRES, 13 February 1987.

35. Rita C. Sagalyn, Director, Space Physics Division, to SD/YC (Col Fratzke), subj: CRRES FY-92/93 Launch Support, 3 November 1986.

36. E. G. Mullen, SPACERAD Program Manager, to AFGL Technical Programs Branch (XOP), subj: Shuttle 24-Month Delay Impact on SPACERAD, 25 July 1986. Interview with E. G. Mullen, 8 June 1987.

37. Ball Aerospace Systems Group, Delta Critical Design Review: Reconfiguration of CRRES for ATLAS/CENTAUR Launch, 11 - 15 July 1988, Boulder, CO. See also Revision D of the CRRES System Description Handbook.

38. See the news story cited below, note 45.

39. Interviews with Edward G. Mullen, 28 July 1988, 19 April 1989, and 21 November 91. For a list of man-years and in-house exploratory development funds devoted to SPACERAD between fiscal years 1982 and 1990, see Appendix B.

40. Memo, Col William F. Fratzke, SD/YC, to AFGL/CC, subj: Transmittal of MOAs, CRRES Agency Tape Generation, 23 October 1985. E. G. Mullen, SPACERAD Program Manager, to SD/YC (Maj Trever), subj: CRRES Tape Management Plan, 8 August 1986.

41. Interview with Robert Raistrick, Data Systems Branch, 5 June 1990. Alan R. Griffin et al., CRRES Agency Tape Generation, Hanscom AFB, MA, October 1989. (AFGL Technical Memorandum No. 174).

42. Interviews with Edward G. Mullen, CRRES/SPACERAD Program Manager, 3 February 1988 and 5 June 1990, and with M. Susan Gussenhoven, Space Particle Environment Branch, 20 June 1990 and 18 September 1991.

43. Agenda, Second CRRES/SPACERAD (ATLAS) Science Team Meeting, 6-7 March 1990, S-Cubed, San Diego, CA.

44. M. S. Gussenhoven et al., "Radiation Belt Dynamics During Solar Minimum," IEEE Transactions on Nuclear Science, Vol. 36, No. 6, December 1989, 2008-2014. For the Satellite Charging at High Altitudes (SCATHA) Program, see the Report on Research at AFGL for the Period January 1979-December 1980, Hanscom AFB, MA, April 1982, pages 99-102.

45. Interview with M. Susan Gussenhoven, Space Particle Environment Branch, 20 June 1990 and 18 September 1991. Interview with David A. Hardy, 10 January 1991.

46. For a listing of MEP chips and components, see Appendix A. Interview with David A. Hardy, 10 January 1991 and with Gary Mullen, 19 April 1989.

47. Colonel Robert J. Hovde, GL/CC to Colonel John E. Armstrong, SSD/CLP, 17 November 1989, and Colonel Armstrong to Colonel Hovde, 12 December 1989.

48. A. R. Frederickson, IDM Test Note, 25 October 1989, CRRES Power Bus Impedance. Interviews with Gary Mullen, 27 February 19 90, and Howard Singer, 17 September 1991.

49. Interview with Gary Mullen, 5 June 1990.

50. Status Report on CRRES Satellite, 13 June 1990. "CRRES Readied for Mid-July Launch after Second Delay," Space News, July 2-8, 1990.

51. The Geophysics Directorate's Atmospheric Sciences Division is participating in an AF/NASA program based at Cape Canaveral to improve detection and prediction of natural and triggered lightning.

52. Conversations with M. Susan Gussenhoven, 12 and 27 July 1990. "Atlas launch delayed by electrical problem," Boston Globe, Tuesday, July 24, 1990, page 44. Paul J. Warden, Capt, USAF, Program Support Manager, Hq Eastern Test Range, Patrick AFB, FL, Memo to Distribution, subj: Post Launch Debriefing on Test 2914, Commercial Atlas/AC-69 [CRRES], 28 August 1990.

53. Geophysics Laboratory Significant Events: CRRES/SPACERAD On-orbit Instrument Checkouts, CSTC, Onizuka AFB, CA, 25 July - 6 August, and again 7 August - 28 August 1990, submitted by E. G. Mullen. Interview with Howard Singer, Space Plasmas and Fields Branch, 10 July 1990 and 5 August 1991.

54. Satellite Status, Satellite Operations: Briefing by Gary Mullen to the Fourth SPACERAD-Atlas Science Team meeting with the Microelectronics Working Group, 23 October 1991.

55. Phone Conversation with Alan Griffin, Data Analysis Branch, 12 August 1991: Agenda for the Fourth SPACERAD-Atlas Science Team Meeting with the Microelectronics Working Group, 23-25 October 1991.

56. C.E. McIlwain, "The Radiation Belts, Natural and Artificial," Science, vol. 142, page 355, 1963.

57. Space Physics Seminar on CRRES Initial Results, presented by Don Brautigam, Space Particle Environment Branch, 17 October 1991.

Space Physics Division: Man Years Devoted to CRRES/SPACERAD

FY-82 through FY87	50
FY-88 through FY-90	25
Total	75

Space Physics Division Exploratory Development (6.2) Funding for CRRES/SPACERAD (Under Project 7601) (in round numbers)

FY-82	$ .3 mill
FY-83	$1.1 mill
FY-84	$1.6 mill
FY-85	$2.3 mill
FY-86	$2.4 mill
FY-87	$2.1 mill
FY-88	$1.9 mill
FY-89	$2.0 mill
FY-90	$2.1 mill
Total	$15.8 mill*

* This includes $800 K "fallout money" and Shuttle recovery dollars put into Project 7601 for CRRES.

Source: E. G. Mullen, SPACERAD Program Manager, December 1987 and August 1991

APPENDIX B

MICROELECTRONICS PACKAGE LIST OF DEVICES AS OF DECEMBER 1986

DUTS FOR SINGLE EVENT UPSET EVALUATION

PART TYPE	PART NUMBER	TECHNOLOGY	QTY.	SOURCE
MICROPROCESSOR	SA3000	CMOS/BULK	6	SANDIA
(3)	SBR9000	IIL	4	TI
	9445	IIL	4	FAIRCHILD
GaAS	256 X 1	GaAS	4	McDAC
(4)	1K X 1	GaAS	4	McDAC
	256 X 1	GaAS	4	ROCKWELL
	1K X 1	GaAS	4	ROCKWELL
VHSIC	32 X 16 RAM	COMMON MODE LOGIC	4	HONEYWELL
(4)	8 K X 9 RAM	N-MOS	4	TI
	4 PORT RAM	CMOS	4	TRW
	8K X 8 RAM	CMOS	4	WESTINGHOUSE
NRL EXPERIMENT	16K X 1 RAM	CMOS/SOS	6	NRL
(2)	512 BIT SR	CMOS/SOS	8	NRL
PROM	6641-8	CMOS	20	HARRIS
(3)	SA2999	MNOS	6	SANDIA
	6616-8	CMOS	10	HARRIS
GATE ARRAYS AND	SBR99S56	IIL	6	TEXAS INSTRUMENTS
SPECIAL	GA2	CMOS/SOS	4	ROCKWELL
(4)	TA11093AG1	CMOS/SOS	4	RCA
	CDI6007	CMOS/BULK	4	CDI
RAMS	PROCESS A,B,C	CMOS	4EACH	JPL
(15)	TA12702D	CMOS/SOS	6	RCA
	SA3240/B	CMOS/BULK	6	SANDIA
	DNA 2K X 8	CMOS	6	HONEYWELL
	71681L70	CMOS/NMOS	6	IDT
	6116RS	CMOS/NMOS	6	IDT
	AM21L47-55DC	NMOS	8	AMD
	AM92L44CDMB	NMOS	8	AMD
	SA3001B	CMOS/BULK	6	SANDIA
	AM93L422DM	LSTTL	4	AMD
	AM93422DM	STTL	4	AMD
	N82S212F/883B	STTL	4	SIGNETICS
	D2164A-20	NMOS	10	INTEL
	HSI-6504-8	CMOS/BULK	10	HARRIS
	HSI-6504RH	CMOS/BULK	10	HARRIS

MICROELECTRONICS PACKAGE LIST OF DEVICES AS OF DECEMBER 1986 (cont.)

DUTS FOR TOTAL DOSE EVALUATION

PART TYPE	PART NUMBER	TECHNOLOGY	QTY.	SOURCE
INVERTERS	CD4007UBH/S	CMOS	8	RCA
(6)	CD4007UBH/SR	CMOS	8	RCA
	CD4007AK/1R	CMOS	8	RCA
	CD4007UBH/SH	CMOS	8	NATIONAL
	4007	CMOS	8	NASA/HARRIS
	F4007/DM	CMOS	8	FAIRCHILD
OP AMPS	LM108AJ/883B	BIPOLAR	4	LTC
(4)	UA308A	BIPOLAR	4	FSC
	PM108AJI/38510	BIPOLAR	4	PMI
	HA2-2600-8	BIPOLAR	8	HARRIS
COMPARATOR (1)	UA139DMQB	BIPOLAR	4	FSC
A-D CONVERTERS	AD573XD	BIPOLAR	4	ANALOG DEVICES
(2)	MN5253H/B	CMOS	8	MICRONETWORKS
HEXFETS (3)	JTX2N6764	HEXFET	4	INTERNATIONAL RECTIFIER
	RFK35N10	HEXFET	4	RCA
	UFN150	HEXFET	4	UNITRODE
OCTAL LATCHES	CD54HCT373F	CMOS	6	RCA
(4)	RB54HCT373C	CMOS	6	SUPERTEX
	SNJ54ALS373J	ALSTTL	6	TEXAS INSTRUMENTS
	54F373DMBQ	FAST	6	FAIRCHILD
JPL CUSTOM	PROCESS A	CMOS	4	JPL
(3)	PROCESS B	CMOS	4	JPL
	PROCESS C	CMOS	4	JPL